# *Social cost-benefit analysis of carbon capture and utilization at biomass plants*

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# Preface

Hillegom, November 2, 2020

After eight months of work, I am proud to present my master thesis. It has been almost ten months since the first meeting with Diederik Notenboom and Gert-Jan Klaase Bos in which they explained the plans for a biomass plant in Rijsenhout. Even though the plans were advanced, the question arose if carbon capture could be a viable option for Meerlanden. Their case and situation formed the base for my proposal and would be ultimately become the foundation of this thesis.

First, I would like to express my gratitude to Jan Anne Annema for his supervision during my thesis. At times of difficulties, his support and insight gave me the motivation to continue. Due to the Coronavirus, a meeting was impossible but Skype was used multiple times to help with this problem. Secondly, I would like to thank Diederik Notenboom for his supervision and input. The comments, ideas, and enthusiasm helped in shaping my master thesis. Furthermore, the weekly Skype meetings were a good motivator in these challenging times. Thirdly, I want to thank Andrea Ramirez for being a part of my thesis committee. Even with her busy schedule, there was time for comments and feedback to further improve my thesis.

Last but not least, I want to thank my family and friends for their motivation and support. Their belief and motivation made it possible to finish my master thesis during these challenging times.

Roy Nekeman

## Summary

Humans have made a significant impact on the world. The built environment, agriculture, transportation, consumption, they all have their share in this impact. Reducing greenhouse gas emissions has been agreed upon by almost all nations in the Paris Agreement (UNFCCC, 2015). To reduce these greenhouse gas emissions diversification away from fossil fuels and innovations in the field of renewables will be required. As most resources have limited availability, reusing these resources will help to limit human impact on the planet. A circular economy will help to close the carbon cycle and further reduce the impact on the environment.

Meerlanden is an innovative and sustainable oriented (raw) material and energy company based in Rijsenhout. Their mission is: “together faster circular”. Their goal is to bring the circular society closer to the citizens (by stimulating and educating on re-use and recycling). From one of these waste streams, the organic waste, the plan arose to investigate the possibilities for a small biomass plant. Generated heat would fulfill the demand in the Schiphol-Rijk area and the facility could be the foundation for a regional heat network. To further reduce $CO_2$ emissions, they are interested in the possibilities for carbon capture. The original plan is to supply the captured $CO_2$ to greenhouses but they want to look beyond this alternative. This research aims to find alternatives for carbon capture and utilization for biomass plants that go beyond supplying $CO_2$ to greenhouses. Supplying $CO_2$ to greenhouses will be used as the reference alternative within the research.

The main research question for this research is: “*To what extent will the implementation of carbon capture and utilization at small biomass plants be beneficial from the business perspective and the perspective of society?*”

To answer this question a literature review, multi-criteria analysis, financial cost-benefit analysis, and social cost-benefit analysis are conducted. The literature review supplies project alternatives and the multi-criteria helps in determining the potentially best project alternatives. A financial cost-benefit and a social cost-benefit analysis were conducted to assess the potential for carbon capture and utilization for Meerlanden.

The multi-criteria analysis showed that two project alternatives, a Compensatiesteen facility or formic acid installation, have the highest score with the weighted criteria. Compensatiesteen is a process in which sand-lime stone bricks are formed under the influence of $CO_2$ instead of heat. In this process, the produced bricks store 250kg $CO_2$ per $m^3$ of Compensatiesteen. This allows for long-term storage of $CO_2$. Formic acid is formed in a direct electrochemical process from the captured $CO_2$. Formic acid can be used in the agricultural industry, but also as a hydrogen carrier in the transport sector. Potentially, formic acid could be used by Meerlanden to drive their heavy-transport vehicles but research is still being conducted to finalize these processes.

The financial cost-benefit analysis shows that the Compensatiesteen alternative has a positive net present value. The formic acid has a significant negative net present value. As both project alternatives include uncertainties, a sensitivity analysis can mitigate a part of the risk involved. The main impact on the net present value of the Compensatiesteen project alternative comes from the assumptions surrounding the raw materials and binding agent required for the process. If costs rise or are assumed incorrectly, a positive net present value will not be reached. The formic acid project alternative is mainly influenced by the electricity price as the process is heavily dependent on a supply of hydrogen formed with electrolysis. As this electricity cost makes up a large part of the operational cost, price changes will have a large impact. From the business perspective, Compensatiesteen could potentially be beneficial but comes with a high level of uncertainty. Precise information about the production process and costs will be necessary to limit the uncertainty involved.

Both project alternatives have a positive environmental impact compared to the reference alternative. In particular, the $CO_2$ savings, help to increase the positive environmental impact. As traditional sand-lime stone bricks are hardened with heat, Compensatiesteen is hardened with $CO_2$. This process stores $CO_2$ and therefore significantly lowers the $CO_2$ emissions caused by the production process compared to traditional production methods. Formic acid via direct electrochemical production also saves a significant amount of $CO_2$ emissions compared to the traditional fossil-based production process. The Compensatiesteen project alternative gets, by the monetization of the environmental effects, an even more positive net present value. The formic acid alternative has a less negative net present value but including the environmental effects is not nearly enough to ensure a positive net present value. Both project alternatives are sensitive to changes in the $CO_2$ pricing as these are the main positive environmental effects. Besides the $CO_2$ pricing, the impact of the binding agent and electricity price also significantly impact the social net present value of the project alternatives.

The research shows that carbon capture and utilization can potentially be beneficial, both from the perspective of society and the business perspective. The high level of uncertainty, following from assumptions and estimations necessary during the research, limits the power of this claim. The details about the production process of Compensatiesteen are not public and large scale direct electrochemical production of formic acid from $CO_2$ does not exist yet. Cooperation with the Ruwbouw groep, the producer of Compensatiesteen, could result in a positive outcome for Meerlanden and Compensatiesteen. Formic acid is an unlikely solution as the difference between product value and operation costs first needs to be bridged. Until the costs involved and the benefits received are closer together, formic acid production will not take place in the Haarlemmermeer.

The reference alternative, supplying captured $CO_2$ to greenhouses, could be the best solution for Meerlanden. Frames has provided information about their carbon capture installation currently operational in Zeeland. As both selected project alternatives include a high level of uncertainty, the low uncertainty (reference) alternative could be the best option. As there are more companies like Meerlanden, the research could be generalized to such companies. Access to own biomass, heavy machinery availability, and shareholding municipalities are the main characteristics of these other companies. Especially access to non-imported biomass could be important in realizing small biomass plants and thereby carbon capture at these facilities. In the last months, as the political climate has shifted, biomass has fallen out of favor in Den Haag. This means that municipalities are not keen on supporting new facilities until the political debate has cooled down. One of the major drawbacks of biomass is the large scale import from other countries. With a small biomass plant designed for regional biomass, the main argument against biomass loses its power.

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# Abbreviations

During this research, some abbreviations are used. Table 1 shows these abbreviations.

*Table 1: Abbreviations*

| Abbreviation | Meaning |
|---|---|
| AHP | Analytic hierarchy process |
| BECCS | Bioenergy with carbon capture and storage |
| CCS | Carbon capture and storage |
| CCU | Carbon capture and utilization |
| FCBA | Financial cost-benefit analysis |
| MCA | Multi-criteria analysis |
| NPV | Net present value |
| SCBA | Social cost-benefit analysis |

# 1. Introduction

## 1.1 Research problem

Humans have made a significant impact on the world. The built environment, agriculture, transportation, consumption, they all have their share in this impact. Reducing greenhouse gas emissions has been agreed upon by almost all nations in the Paris Agreement (UNFCCC, 2015). To reduce these greenhouse gas emissions, diversification away from fossil fuels and innovations in the field of renewables will be required. As most resources have limited availability, reusing these resources will help to limit human impact on the planet. A circular economy will help to close the carbon cycle and further reduce the impact on the environment.

Biomass can play a temporary role in the reduction of greenhouse emissions when implemented under the right circumstances (Scarlat *et al.,* 2015). The Netherlands has more than 200 biomass plants (AVIH, 2020). Most of them relatively small, but some of them are large energy plants operated by the main energy companies. To be part of the circular economy, biomass should be sourced locally. This limits the possibilities there are for biomass. According to the European Commission (2012), the potential for woody biomass in the Netherlands is one of the lowest in the European Union. The limited amount of forests and land have a severe impact on the availability of this type of biomass for energy generation. Large-scale energy plants can therefore not operated based on locally sourced biomass. Small scale plants can fill in this gap. Combining small biomass plants with carbon capture can further reduce greenhouse gas emissions from energy generation (Scarlat *et al.,* 2015).

The case for this research is provided by Meerlanden. Meerlanden is an innovative and sustainable oriented (raw) material and energy company based in Rijsenhout. Their mission is: “together faster circular”. Their goal is to bring the circular society closer to the citizens (by stimulating and educating on re-use and recycling). They want to bring all waste back into the cycle. From a traditional waste handling company, Meerlanden transformed towards an innovative waste collection and handling company that unburdens nine municipalities in the Netherlands of their public space management. Moreover, they try to increase the value of different waste streams by reusing and recycling as much of the commodities as possible and contributes to a cleaner environment. From one of these waste streams, the woody biomass, the plan arose to investigate the possibilities for a small biomass plant. Generated heat would fulfill the demand in the Schiphol-Rijk area and the facility could be the foundation for a regional heat network. To further reduce $CO_2$ emissions, they are interested in the possibilities for carbon capture. As innovation in the field of carbon capture can still lead to extensive cost reductions (Størset, 2019), it offers possibilities for Meerlanden to ‘close the cycle’. The case used during the research as provided by Meerlanden will be further explained in chapter 2.

The OCAP (*organic $CO_2$ for assimilation by plants*) network is the $CO_2$ network built around the former oil pipeline between Rotterdam and Amsterdam. Meerlanden already has made preparations to be connected to the OCAP network because of its green gas facility. When upgrading biogas to green gas at their facility, 3000 tons of $CO_2$ becomes available for use each year. This $CO_2$ could be combined with the $CO_2$ from the biomass plant and offered to greenhouses via the OCAP network. These are preliminary plans so more effective ways of $CO_2$ use need to be analyzed to find the best solution for Meerlanden. With changing technologies, creating more useful or more desirable products could be a possibility to implement with the new facility and carbon capture installation. Due to the small scale of the whole operation, research needs to be done to identify the possibilities for $CO_2$ utilization and what role carbon capture and utilization can play in reducing carbon emissions in the short term. This research will be carried out as a thesis project within the Engineering and Policy Analysis master program of Delft University of Technology. Research into the potential of $CO_2$ capture at biomass plants combined with different utilization possibilities for the $CO_2$ fits very well within the Engineering and Policy Analysis program. The research can lead to a broader scientific contribution to $CO_2$ capture and utilization at biomass plants and policy advice for Meerlanden.

## 1.2 Research gap

Providing greenhouses with $CO_2$ from biomass plants can help in limiting the amount of emitted $CO_2$. Bioenergy with carbon capture and utilization offers pollution to solution alternatives (Rahman *et al.,* 2017). They describe that the combination of CCS (carbon capture and storage) with biofuel production can help to mitigate $CO_2$ emissions while not affecting crop production. The problem with this solution is that still $CO_2$ is being emitted when it is preferred to avoid $CO_2$ emissions if possible. Bioenergy with carbon capture and storage (BECCS) is, therefore, another option. Azar *et al.* (2010) concluded that policymakers should be cautious when looking into this technology. It helps to postpone $CO_2$ emissions but will not be the primary measure to reach the $CO_2$ targets.

Bioenergy and CCS offer solutions for $CO_2$ mitigation. The combination of these technologies is relatively new and not well researched as biomass remains a small part of the total energy consumption. Underground storage of $CO_2$ does not offer the benefits of utilization. Bioenergy with carbon capture utilization that stores carbon for a longer period could, therefore, be the most desirable solution. These so-called BECCUS would utilize carbon in such a way that it would store carbon for a longer period. The combination of carbon capture with different forms of utilization has different outcomes. As small biomass plants have other criteria and difficulties, the solutions will be different compared to carbon capture at large scale energy plants.

The financial and societal effects of carbon capture and utilization are important for assessing the viability of the proposed solutions. As companies need profit to survive, financial cost and benefits are the main factors for them when deciding to invest in new technology or facilities. Beyond these financial effects are social effects. These social effects can be difficult to monetize but can contribute to the viability of carbon capture and utilization from a societal perspective. Especially for companies like Meerlanden that look beyond the financial impact of investment and try to increase social welfare.

The combination of the different impacts of carbon capture and utilization provides a research gap. The point where the financial, social and all the criteria belonging to small biomass plants come together to provide a solution. But this is a niche part of the overall research into carbon capture and utilization and therefore not well researched.

## 1.3 Research questions

The research aims to find new combinations that will help to reduce the knowledge gap and lead to new opportunities for Meerlanden and other companies looking into the implementation of carbon utilization at biomass installations. The following questions will be addressed in this research to find the desired answers.

The main research question in this study is as follows:

*To what extent will the implementation of carbon capture and utilization at small biomass plants be beneficial from the business perspective and the perspective of society?*

To find the answer to the main research question, three sub-questions will be used:

**SQ1:** *What are the potential alternatives of carbon utilization for Meerlanden?*

There are a lot of possibilities for carbon utilization but not all are suited for Meerlanden or small biomass plants. A screening is required to select several alternatives that will be used for the rest of the analysis. Based on a range of criteria, the alternatives with the biggest potential will be selected from the screening.

**SQ2:** *What are the financial consequences for Meerlanden?*

Even though Meerlanden wants to increase its regional social impact, it remains a company. The proposed project alternatives need to be analyzed from the business perspective besides the perspective of society. As external or indirect effects will not lead to a direct increase in revenue for Meerlanden, the financial consequences of the proposed project alternatives are important to estimate the feasibility of project alternatives.

**SQ3:** *What are the social costs and benefits of the different carbon capture and utilization options?*

Meerlanden wants to increase its social impact in the region and have a positive contribution to society. Looking beyond the traditional financial analysis will provide an insight into the social welfare change due to the proposed project alternatives.

## 1.4 Thesis overview

The research is conducted to generate advice for Meerlanden and to answer the main research question. Literature review, multi-criteria analysis, and social cost-benefit analysis are the main research methodologies. The literature review will help in identifying the different possibilities for carbon capture and utilization. When these alternatives are identified, the best scoring alternatives will be selected using a multi-criteria analysis. When these best scoring project alternatives are selected, a social cost-benefit analysis will tell if carbon capture and utilization can contribute to a social welfare increase. These methodologies will be described in chapter 2. Meerlanden provides the case for this research, which is described in chapter 3. Chapter 4 contains the literature review and multi-criteria analysis. Chapter 5 will describe the setup for the cost-benefit analysis. Chapter 6 will show the financial implications of carbon capture and utilization for Meerlanden. Chapter 7 describes the impact of carbon capture and utilization for Meerlanden and society. The main conclusions and recommendations will be shown in chapter 8 and the research will end in chapter 9 with the discussion and reflection. Figure 1 shows the overview and research structure.

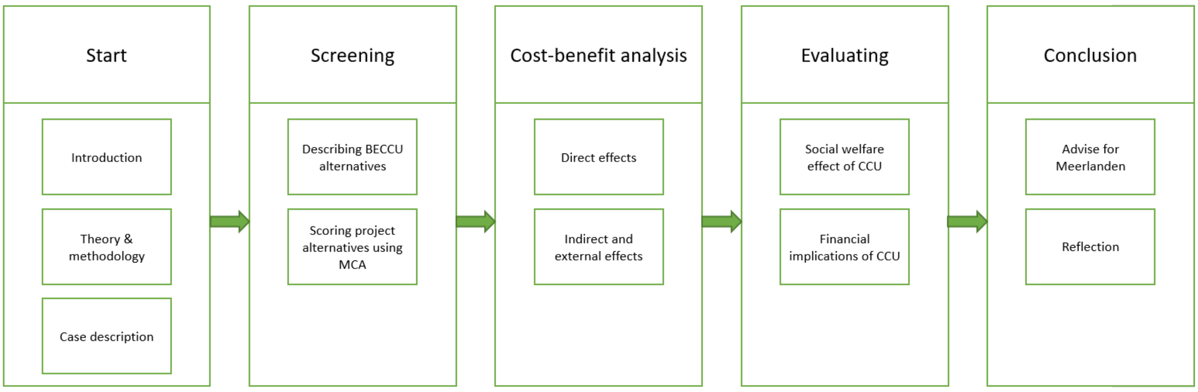


*Figure 1: Research structure*

# 2. Methodology

The methodology that will be used to answer the research questions will be discussed in this section. This thesis is based on the problem set by Meerlanden. The case study method will be used to answer the set questions which will be explained in 2.1. A literature review will be used to supply the required information for all three sub-questions. Section 2.2 will discuss the use of the literature review for both. After the formation of CO2 capture and utilization alternatives, selecting the most viable alternatives will be done by using multi-criteria analysis (2.3). As the multiple value creation is an important part of assessing the possibilities for CO2 capture and utilization at small biomass plants, a social cost-benefit analysis will be performed. The method of such a social cost-benefit analysis will be discussed in section 2.4. Table 2 shows an overview of the methods used to answer the sub-questions.

*Table 2: Overview of sub-questions with methodologies*

| | Question | Methods |
|---|---|---|
| **SQ1** | What are the potentially best alternatives of carbon utilization for Meerlanden? | Case study, Literature review, Multi-criteria analysis |
| **SQ2** | What are the financial consequences for Meerlanden? | Case study, Financial cost-benefit analysis |
| **SQ3** | What are the social costs and benefits of the different carbon capture and utilization options? | Case study, Literature review, Social cost-benefit analysis |

## 2.1 Case study

According to Baxter and Jack (2008), qualitative case study methodology provides tools for researchers to study complex phenomena within their contexts. The method used in this research will be a single in-depth case study to evaluate the impact of carbon capture and utilization. The case is about Meerlanden and its planned small biomass plant. Examining all small biomass plants and the possibilities for carbon capture and utilization in the Netherlands would be impossible in the scope of this research. By using the case study methodology, knowledge can be gathered about the implications of carbon capture and utilization. Meerlanden has its specific characteristics in terms of goals, facilities, resources, and stakeholders. This can make it difficult to generalize the results from an in-depth case study to an overall conclusion for all small biomass plants. Therefore, this is the main drawback of using an in-depth case study.

## 2.2 Literature review

Xiao & Watson (2017) described a literature review as an essential feature of academic research. As academic research is built on prior work, getting a good overview of the information available is important for conducting good research. It helps with identifying and exploring different methods, techniques, and new developments in the field of carbon capture and utilization.

The main drawback of conducting a literature study is that one can only find information about technology or developments that have been researched before and have been published. Furthermore, some specific information about business cases for (relatively) new technologies can be unavailable. Companies can be reluctant to share this information in public literature because of competition and development costs.

For each sub-question, other information is required to answer it. Table 3 describes the partial elements of the question and the search words that can be used to find relative information. Google scholar will be the primary mean of finding the relative literature. After the initial search, more complex combinations of search can be used. Furthermore, the snowballing technique will be used to gather additional literature.

*Table 3: Search plan for literature review*

| Question | Partial elements of the question | Search words |
|---|---|---|
| SQ1: What are the potentially best alternatives of carbon utilization for Meerlanden? | Carbon capture | Carbon capture, CCS, pre-combustion, post-combustion, oxy-combustion, sequestration |
| | Carbon utilization | Industrial ecology, CCU, chemical utilization, carbon mineralization, biological utilization, |
| | Biomass plant | BECCS, BECCU, small biomass plant |
| SQ3: What are the social costs and benefits of the different carbon capture and utilization options? | Carbon utilization costs | Social costs, carbon utilization costs |
| | Carbon utilization benefits | Chemical prices, demand synthetic fuel |

## 2.3 Multi-criteria analysis

The literature study will be used to gather several options in terms of carbon utilization that can be formed into project alternatives for small biomass plants in combination with carbon capture. This screening cannot only be based on a literature study, therefore an MCA will be conducted. Dodgson, Spackman, Pearman, & Phillips (2009) created an extensive manual for multi-criteria analysis used by multiple governmental organizations. Its decision-making process when dealing with a multi-criteria analysis will also be used for this research.

- Identifying objectives
- Identifying options for achieving the objectives
- Identifying the criteria to be used to compare the options
- Analysis of the options
- Making choices
- Feedback

The objective of this research is to find beneficial ways of combining small biomass plants with carbon capture and utilization. As described before, there will be multiple options for achieving these objectives which will be formed into alternatives for the specific case.

## Analytical hierarchy process

The analytical hierarchy process is a technique for decision making in complex environments (Vargas, 2010) and is chosen to be used for determining the weights in the multi-criteria analysis. Figure 2 shows an example of a hierarchy of criteria. The main goal has multiple criteria to help in the selection of the best alternative. By using pair-wise comparison for each of the chosen criteria, the impact of these criteria on the alternatives can be assessed. The comparison will be based on expert judgment. As the strategic advisor of Meerlanden, Diederik Notenboom will assist in providing these comparisons and thereby the weight estimations for the MCA.

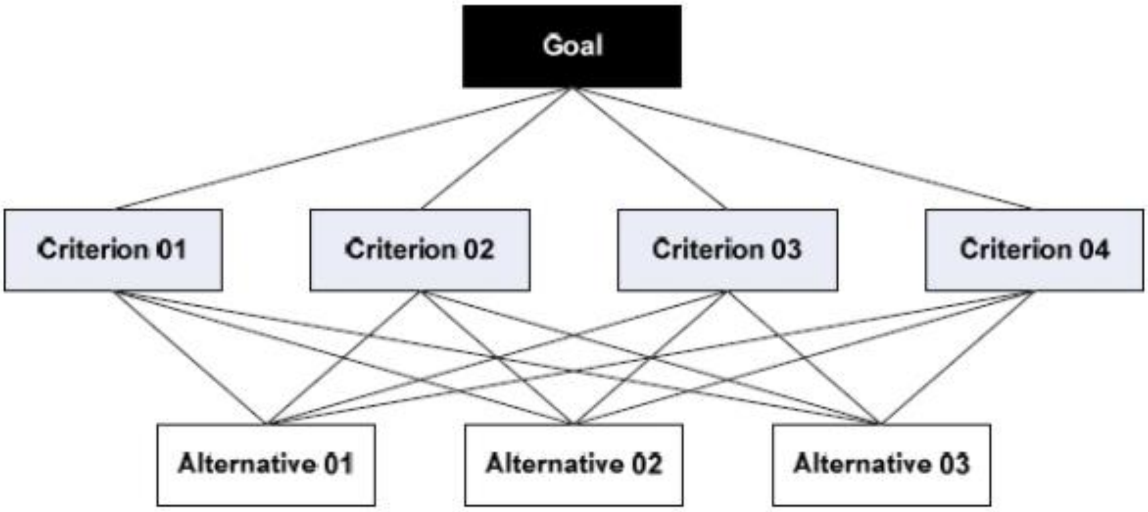


*Figure 2: Example of a Hierarchy of Criteria/Objectives (Vargas, 2010)*

The pair-wise comparisons are based on the importance of a criterion over another criterion. The levels of importance that will be used are shown in figure 3. To make the pair-wise comparisons easier to conduct, a 'questionnaire' is used. The questionnaire contains all the necessary comparisons required to assess the weights of the criteria. Appendix D contains the used questionnaire for the analytical hierarchy process.

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal Importance | Two activities contribute equally to the objective. |
| 3 | Moderate importance | Experience and judgment slightly favor one activity over another. |
| 5 | Strong importance | Experience and judgment strongly favor one activity over another. |
| 7 | Very strong or demonstrated importance | An activity is favored very strongly over another, its dominance demonstrated in practice. |
| 9 | Extreme importance | The evidence favoring one activity over another is of the highest possible order of affirmation. |

*Figure 3: The intensity of importance (Saaty, 1994)*

The pair-wise comparisons will be transformed into numerical values. With these values, the different weights of the criteria can be assessed which will be part of the multi-criteria to assign a score to each alternative.

## 2.4 Social cost-benefit analysis

Policymaking is about making choices and every choice can have a range of different effects. Cost-benefit analysis (CBA) is an economic evaluation method, that is most commonly used in the public sector, that can be used for the appraisal of projects. Two types of CBA are applied. First, a financial cost-benefit analysis (FCBA) that looks from the business perspective if the financial benefits justify the proposed investment (and other costs) over the life span of the project. Second, the social cost-benefit analysis (SCBA) that is used to look if the project will contribute to social welfare. Estimating social welfare contribution depends on a range of welfare effects which are described in table 4. The SCBA will be the core of the research but naturally, an FCBA will be part of the research. By estimating the financial feasibility of the proposed projects, essentially an FCBA will be conducted. The difference will be that the FCBA is part of the SCBA.

*Table 4: Effects SCBA (Romijn & Renes, 2013)*

| Effect type | Description | Example |
|---|---|---|
| Direct effects | Effects that can be directly linked to the stakeholders of a project. | The reduction of transport costs because of the newly built access route to the facility. |
| Indirect effects | Effects that are passed on to the stakeholders in other markets that are not directly involved in the project. | Lower transport costs are passed on to the customers by reducing the selling price. |
| External effects | Effects that reach actors outside of the market. | Because of the newly built access route with increased traffic, there is an increase in Greenhouse gas emissions, noise pollution, and air pollution. |

Properly assessing these effects is the main challenge of an SCBA. Romijn & Renes (2013) describe methodological steps on how to conduct an SCBA to deal with these challenges. The following methodological steps were used:

1) **Problem analysis**: The main problem derives from the case as set by Meerlanden. This will be further described in chapter 3.
2) **Reference alternative**: The reference alternative also follows from the case. Carbon capture and delivery of that $CO_2$ to neighboring greenhouses was the original plan. This will be used as the reference alternative and will be further explained.
3) **Define project alternatives**: Project alternatives will follow from literature research and screening for possibilities with some conditions by Meerlanden. The MCA will eventually determine which project alternatives will be used in the SCBA.
4) **Determine the effects and benefits**: Data will be an important part of determining the effects and benefits of the project alternatives. Literature research will supply a large part of the required data. Additionally, Meerlanden can supply data regarding social impact as they have

experience in projects that are focused on increasing social welfare. Specifically in projects for people with a distance to the labor market. This could play a role in certain project alternatives and can thereby help in providing data regarding social welfare increase.

5) **Determine the costs**: Data for determining the costs will be mainly based on literature research. Companies can be reluctant in providing specific data about costs as this can negatively impact their business case. Public data about investment costs can help in estimating the costs but precise data will be unlikely to be found. Estimations will be based on the parameters of the biomass plant and carbon capture installation and scaling will be done accordingly.
6) **Variants and uncertainty analysis**: This step will function as a sensitivity analysis. By changing the parameters of the SCBA model, other variants can be created to test the sensitivity of the model. It will help in determining the robustness of the SCBA.
7) **Set up an overview of costs and benefits**: When both the costs and benefits are properly assessed, they can be put in an overview. This makes it possible to compare the costs to the benefits and create results.
8) **Present results**: The comparison between the costs and benefits from the overview can be presented.

# 3. Case description

The research into carbon capture and utilization at small biomass plants will be based on an in-depth case study. Section 3.1 will start with a description of Meerlanden, the company that provided the case. Section 3.2 continues with a description of the planned biomass installation and section 3.3 will highlight the set condition for carbon capture and utilization by Meerlanden. Finally, the proposed carbon capture installation will be described in section 3.4.

## 3.1 Meerlanden

Meerlanden is the company that will be used for the case study as mentioned before. Meerlanden is an organization formed in 1997 from different municipal services. They provide services (waste collection, road de-icing, public space management, etc) to 29 different municipalities and 3800 companies in the region Schiphol, Bollenstreek, and Zuid-Kennemerland (Meerlanden, 2019). Most of these municipalities are also shareholders in Meerlanden N.V. They have multiple long term goals in working towards a circular economy. As they are a company in the first line after the inhabitants, they see a lot of possibilities for more sustainable use of resources.

Their main office, and largest waste collection point, is located in Rijsenhout. This is also where the majority of garbage trucks have their base and drop off when full. Collecting organic waste is also a big part of their service. To increase the use of the collected organic waste, they have built a composter to process this type of waste into biogas, compost, and 4 other products ($CO_2$, water, heat, and citrus oil). Figure 4 shows the current process of handling organic waste.

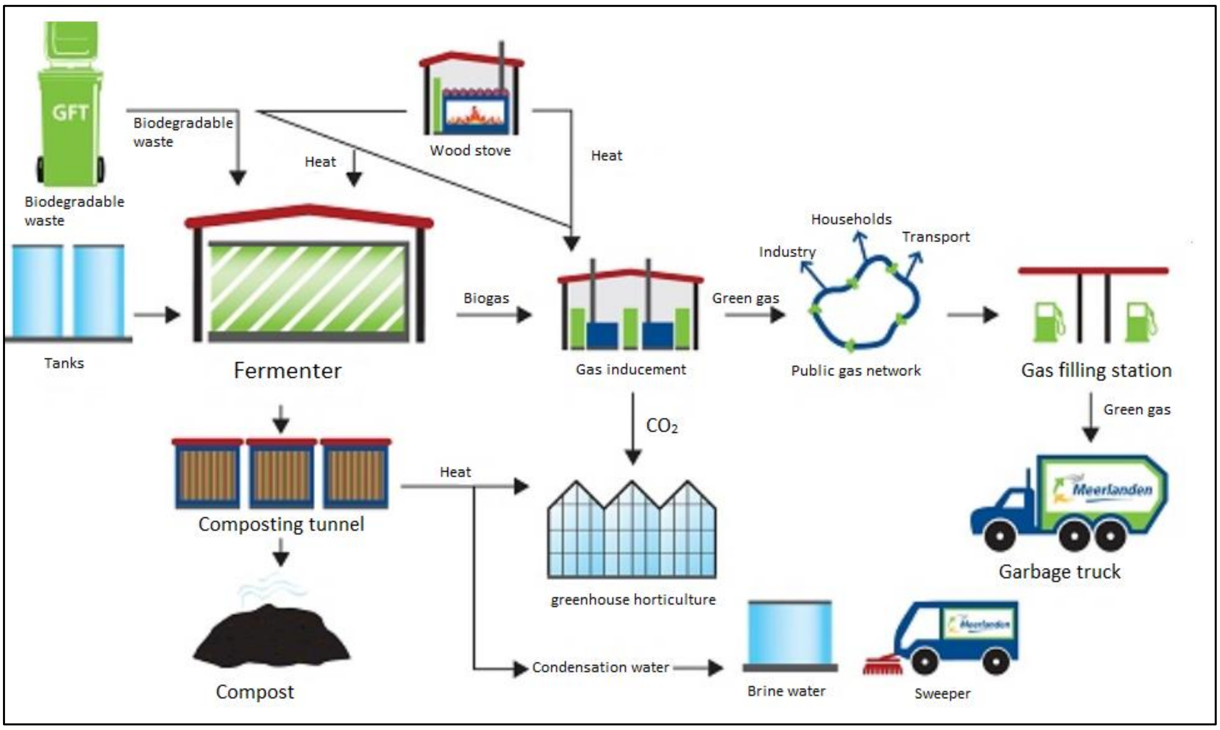


*Figure 4: Organic waste process (Meerlanden, 2020)*

The biogas is converted into green gas by removing $CO_2$. After checks and the addition of safety features to the green gas, the green gas gets added to the national gas infrastructure to be used in households or businesses. The compost can be collected by residents to fertilize their gardens for example. By adding these facilities, collected organic waste gets a new purpose within the region which helps Meerlanden in working towards a more circular economy. There is no use yet for the 3000 ton per year of $CO_2$ that becomes available when upgrading the biogas to green gas. Meerlanden has made preparations to deliver this $CO_2$ to the OCAP network. When looking into alternatives for carbon utilization, this amount of $CO_2$ is ready to be used and can be incorporated into the alternative as an extra source of $CO_2$.

Meerlanden its initial plan was to use this $CO_2$ as a contribution to the OCAP network. The OCAP network is a 'refurbished' old oil pipeline between Amsterdam and Rotterdam. It has found a new purpose as the mainline for the $CO_2$ network that Linde is setting up. The two main sources of $CO_2$ are now located in Rotterdam port but demand is more in the Westland area. Therefore, the OCAP network was interested in extra sources of $CO_2$ (even though it is a relatively small amount of $CO_2$) to stabilize their network. Meerlanden has finished their part of the connection but the final connection point from the OCAP network to Meerlanden has not been realized yet. This allows using this $CO_2$, that is already available, for other forms of carbon utilization instead of delivery to greenhouses.

## 3.2 Planned facility description

The whole research involves the planned small biomass plant as planned by Meerlanden. When Meerlanden was looking into further incorporating the circular economy in their business strategy, they concluded that they had a surplus in woody biomass. With Schiphol-Rijk nearby, this allowed creating the basis for a local heat network. The hotels and offices located at Schiphol-Rijk can become more sustainable and Meerlanden has a new purpose for their woody biomass. This has been incorporated into their new strategy for 2021. Figure 5 shows a summary of their green waste strategy.


*Figure 5: Meerlanden 2021 organic waste strategy*

The biomass plant will be the main planned facility that will be the center of all the other new initiatives. The business case is based on two 3,5 MW boilers (wood chips) and one 3,5 MW backup boiler (gas). Two woodchip based boilers will be sufficient for most of the year to supply the required heat for the network (Meerlanden, 2020). During longer cold periods in the winter and thereby peak heat demand, the two boilers can not fully fulfill the demand for heat. The gas boiler can provide the necessary extra amount to ensure stability in the network. Furthermore, the gas boiler can be used when maintenance is required in one of the other boilers. This ensures stable operation and sufficient heat generation. In addition to these boilers, two hot water buffers will be based next to the installation. These two silos of 10 meters in diameter and 14 meters in height will function as a storage for the generated hot water. The combination of both storage capability leads to 150 GJ in potential heat storage (Meerlanden, 2020). These storages limit the effect of a decline in heat demand and help to endure peak heat demand.

Emissions are an important part of the energy project. Both the woodchip boilers and the gas boiler are designed with a combustion temperature of 1000°C to minimize emissions. In the end, the yearly $CO_2$ emissions will be around 7000 tons (Meerlanden, 2020). This will mainly depend on the moisture content and wood mixture. To comply with the regulation for NOx emissions, urea injection will be used. The urea injection will ensure that the NOx emissions will be lower than 70 mg/m3 in the flue gas of the facility (Meerlanden, 2020). SOx emissions will be limited to a maximal 3 mg/m3 by the optimal combustion temperature (Meerlanden, 2020). Particulate matter will be limited to 3 mg/m3 with the use of the proper filter cloths (Meerlanden, 2020).

The feedstock is an important aspect of the planned facility. The planned demand, according to the project description, is around 9000-ton of dry woody biomass per year (Meerlanden, 2020). Mainly based on prunings from the region and turned in wood from waste collection points (only clean wood). Meerlanden can provide 70% of the required biomass. The other 30% will be provided by subcontractors and the municipality of Haarlemmeer. In addition to the bunkers for the biomass, a wood dryer will be realized. This installation will have a capacity of 20000-ton 'wet' biomass per year, which ensures sufficient dry biomass for the biomass installation as almost half the weight is lost during the drying process (Meerlanden, 2020). The wood dryer will ensure the correct moisture content of the woodchips to limit the emissions when burned in the biomass installation. The required heat for the wood dryer will be sourced from the composter.

## 3.3 Conditions for carbon capture and utilization

Meerlanden is not a high-tech company or a chemical producer. For the creation of project alternatives, they have explained some conditions that are important to them. This ensures that project alternatives can be executed by them.

First of all, installations need to function with minimal human involvement. When personnel is needed, it should be of similar complexity as their other facilities. As described earlier, they already have a green gas facility that functions with minimal human involvement. If project alternatives would involve a lot of complex human involvement, this would require the type of personnel that they do not employ yet. Therefore, project alternatives with minimal human involvement and relatively low complexity (when operating) are desired.

Secondly, if installations are self-financing (cost equal to benefit) but have a significant positive social impact, an investment can be made. This is in line with the definitions of an SCBA but was mentioned explicitly. They are working on creating a more circular and sustainable company with a large positive social impact. With municipalities as the main stakeholders, financing is also not an issue when a positive social impact can be made with a project alternative.

Thirdly, products created from captured $CO_2$ should have (if possible) a local demand because Meerlanden wants to increase its local impact. Furthermore, regionality is becoming an increasingly important part of their business. Local biomass to local used $CO_2$ is the base for the research and which is in line with the strategy of Meerlanden. These can either be used by Meerlanden or be useful to companies/consumers in the area. It is not strict conditions but a project alternative that has products that can be used in the region would be highly desirable.

## 3.4 Proposed carbon capture installation

The research will not be focused on the carbon capture installation itself. Appendix A describes a range of potential carbon capture technologies that could, theoretically, be used at a biomass plant. Frames B.V. has built an operating and proven carbon capture installation with similar characteristics to the biomass plant as planned by Meerlanden. They have provided information (investment costs and operation costs) about their facility that other manufacturers are not willing to share. The proposed plant by Frames is a post-combustion absorption-based carbon capture process. It uses Galloxol as its main solvent in the capture process. They have installed this installation in Zeeland for a corporation of greenhouse farmers. This facility also has a thermal capacity of 7 MW (similar to the plant proposed by Meerlanden) and is biomass-based (Duurzaambedrijfsleven, 2019). Figure 6 shows the schematic process of the carbon capture installation that Frames proposes.

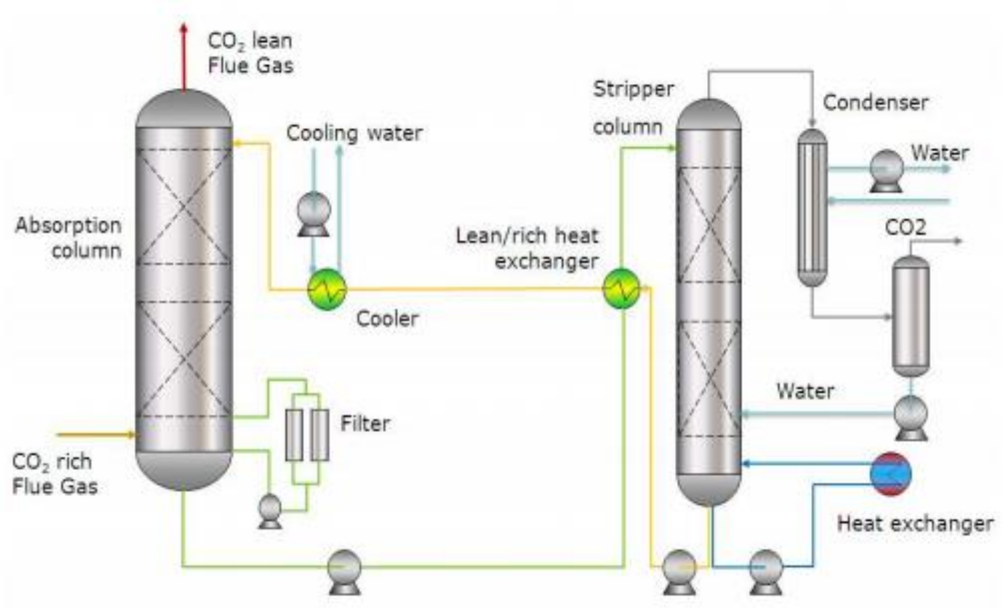


*Figure 6: Schematic process of Galloxol based carbon capture (Frames, 2020)*

The two main parts of the process in figure 6 are the absorption column and the stripper column. $CO_2$ rich flue gas enters the absorption column at the bottom. The absorption column holds the Galloxol that 'captures' the $CO_2$ from the flue gas. The absorption column holds interfaces where the gas and liquid meet and the $CO_2$ is passed over into the liquid. This chemical reaction ensures that almost all $CO_2$ is removed during the distance from the bottom to the top of the column. The result is $CO_2$ lean flue gas and a $CO_2$ rich Galloxol liquid. This $CO_2$ is 'cooked' out of the Galloxol liquid in the stripper column. By adding heat and water, the $CO_2$ is removed from the Galloxol mixture in the stripper column. The technology provides solutions for multiple applications, markets and promises high-quality $CO_2$ (Frames, 2020). At least 90% $CO_2$ concentration can be reached but this concentration can be higher based on customer requirements (Frames, 2020). As Galloxol technology can also be used in the food sector, a higher $CO_2$ concentration can be made possible (Frames, 2020).

### *Costs*

As different carbon capture technologies could be used, this will be left out of the analysis. For the analysis, the assumption will be made that the carbon capture will be based on the specification provided by Frames B.V. Frames B.V. also provided a price list that goes along with its technology and installation. These costs for the carbon capture will be used in the FCBA and SCBA to determine the cost of carbon capture. The focused can thereby remain on the research of different utilization alternatives. They have two installations available with different capacities, with price-levels for the Netherlands in July 2020.

CAPEX for a *standard* 2,2 ton/hour $CO_2$ capture installation:

2,6 M€ without gas balloons (ca. 0,5 M€) and civil activities (ca. 0,25 M€)

CAPEX for a *standard* 4,4 ton/hour $CO_2$ capture installation:

3,9 M€ without gas balloons (ca. 0,9 M€) and civil activities (ca. 0,35 M€)

The business case from Meerlanden and its biomass plant is based on 4000 operating hours. With 2,2 ton/hour $CO_2$ capture, the standard smaller carbon capture installation would be sufficient. The size of the installation mainly influences the operating costs of carbon capture. Figure 7 shows the operating expenses provided by Frames for the 'smaller' 2,2 ton/hour carbon capture installation. It is important to note that this system does not include the cost of possible necessary compression.

**Chemical consumption and cost**

| Name | Price per unit[1] | Price per ton produced $CO_2$[2] |
|---|---|---|
| Galloxol® | € 4.500,00 /ton | € 1,10 |
| Glycol | € 1.900,00 /ton | € 0,12 |
| Water | € 0,80 /ton | € 0,10 |

| Name | Price per unit | Price per extracted MWh[3] |
|---|---|---|
| Caustic | € 400,- /ton | € 2,60 |

**Power**

| Name | power/ton of produced $CO_2$ |
|---|---|
| Electrical power | 60 kWh |
| Heat taken from the Vyncke boiler[4] | 3,5 MW |
| Heat recovered from the Galloxol® $CO_2$ plant[5] | >90% |

[1] Price-level for the Netherlands, July 2020.
[2] This is an average estimate based on realistic operational conditions. Actual values may vary over time and are a function of biomass quality, thermal properties, maintenance of the biomass boiler and Galloxol® CO2 plant, environmental conditions, etc.
[3] Max 1 MW heat can be obtained additionally from the 7 MW boiler by cooling flue gases in the Condenser, Caustic is needed to neutralize the produced condensate.
[4] Heat can be in the form of saturated steam at 3bara or hot water at 4bara/140ºC.
[5] Heat recovered is in the form of hot water above 70ºC.

*Figure 7: OPEX Galloxol carbon capture (Frames, 2020)*

# 4. Carbon utilization screening

This chapter will involve the screening of the carbon utilization options. From this screening, project alternatives can be formulated for Meerlanden and with the use of the multi-criteria analysis, the potential alternatives can be evaluated. The best scoring project alternatives will be used in further analysis to determine the possibilities for Meerlanden and small biomass plants in general.

## 4.1 Carbon utilization

The literature review is used to determine the different carbon utilization paths that could be included. Appendix B shows the literature review tables that hold the literature on which the diagram in figure 8 is based.

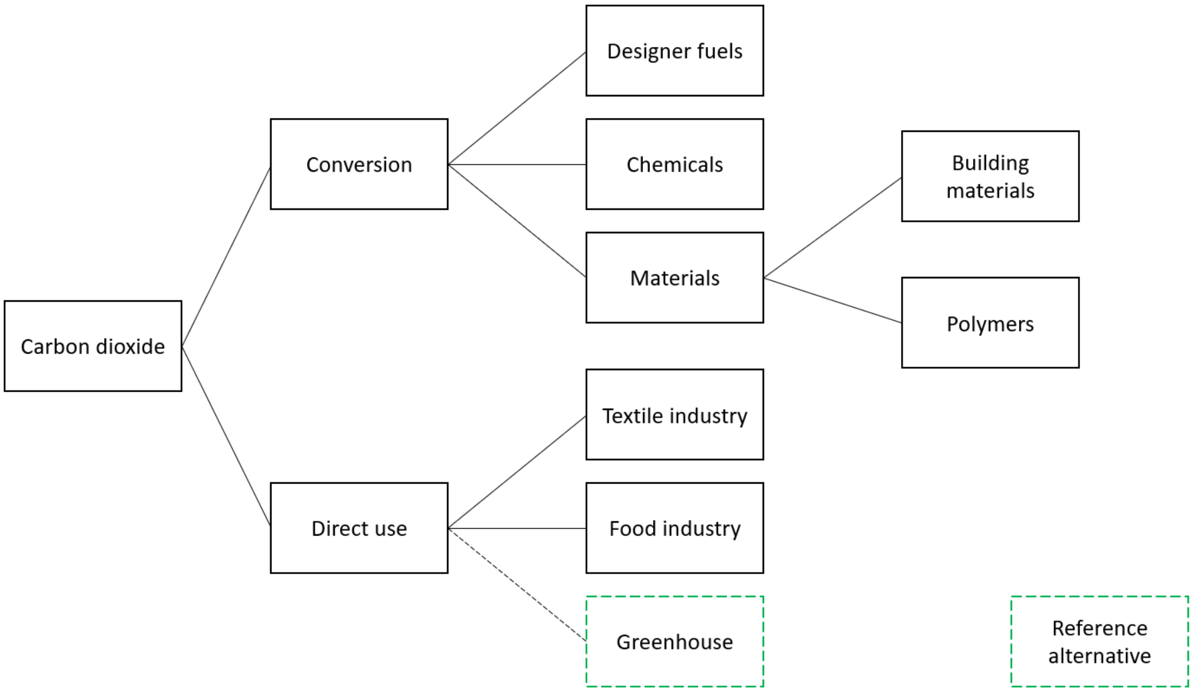


*Figure 8: Diagram of carbon utilization paths*

The carbon capture installation is left out of this evaluation. The assumption is made that the installation from Frames will be installed and can deliver a certain amount of $CO_2$ to be used in the utilization process. There are two main pathways to use the capture $CO_2$. This is either direct use of $CO_2$ or conversion. Direct use is also the path that Meerlanden first envisioned when looking into the use of $CO_2$ in greenhouses. Delivery of capture $CO_2$ to greenhouses is therefore the reference alternative. Other options for direct use of $CO_2$ are in the textile industry and food industry. The path of direct use is the least 'complicated' as gaseous $CO_2$ is the product which is directly available after capture. For storage or transportation compression could be required but there will be no extra chemical processes needed besides the compressing. The other main path is chemical conversion which requires additional steps to generate added value. Designer fuels, chemicals, and materials can all be made from $CO_2$ under the right circumstances. Materials can either be building materials (like limestone bricks) or polymers (plastics). A pre-selection is made of different project alternatives that will be further evaluated later in the screening process.

## 4.2 Potential regional demand for carbon-based products

Meerlanden has the desire to become a more circular and sustainable company with a strong focus on regionality. With a strong focus on regionality, the potential demand for carbon-based products plays a large role. This section will focus on some potentially large users of the to be created products.

*Meerlanden*

Meerlanden is looking to further decrease its carbon footprint. The fleet of garbage trucks and other vehicles gets steadily replaced instead of instant replacement. They are looking into new possibilities to drive greener vehicles. Currently, most garbage trucks drive on CNG which has relatively low emissions. Replacing them with hydrogen, electric, or other fuel-based trucks can be an option if the right circumstances are there.

*Schiphol*

Schiphol wants to severely decrease its carbon footprint to comply with the regulations set by the national government. Electric taxiing is tested and will be implemented soon to decrease a significant amount of emissions that take place at the airport (Parool, 2020). Supplying Schiphol and interested airlines with synthetic kerosene could be a possible option. Rijsenhout is almost next to Schiphol and Meerlanden could have the possibility to produce synthetic kerosene. This would ensure demand for the product that Meerlanden would be creating and help in closing the business case for this carbon utilization alternative.

*Shareholding municipalities*

As mentioned before, the shareholders of Meerlanden are eight of the serviced municipalities. These municipalities also have the task of decreasing their emissions. This could lead to more cooperation in multiple alternatives. Synthetic petrol for municipality-owned vehicles or the vehicles that Meerlanden uses in those municipalities. Furthermore, in the area around Rijsenhout and some of these municipalities, large plans are made for new neighborhoods. In total, around 30000 houses are planned to be built in this area. This would open up opportunities for the production of, for example, $CO_2$ based limestone bricks that could be used to façade those to be built houses. This would ensure demand for the product and would be good for the municipalities in decreasing their emissions.

## 4.3 Screening criteria

The criteria will be an important part of the MCA. When screening the project alternatives and making a selection of the most viable project alternatives, the criteria will eventually determine which project alternatives will be selected for further analysis. The criteria are based on literature and the expert opinion from Diederik Notenboom, the senior strategic advisor at Meerlanden. A selection of criteria will be used to conduct the MCA.

This could lead to differences in the selection of alternatives between different cases. As every case has its circumstances, resources, and preferences, these differences in selection will be explainable by these different characteristics. These differences can also provide better opportunities if the circumstances are better.

### 4.3.1 Investment costs

Investment costs have a direct impact on the financial viability of a project alternative. When looking into carbon capture and utilization, large investment costs can be a problem. Even though higher investment costs can lead to significantly lower operating costs, high investment costs can increase the difficulties and risks involving a proposed project alternative. Diederik Notenboom, an expert from Meerlanden, described that high investment costs will not necessarily be a limitation but will be important to take into account when comparing project alternatives.

The investment costs of the different project alternatives will be based on the CAPEX of existing or planned installations, depending on which information is available. The retrieved cost estimations will be projected as investment costs per ton of yearly captured $CO_2$. With a yearly capacity of 10000 tons of $CO_2$ at Meerlanden, these estimations can be used to assume the total investment costs involved in the project alternatives in the later analysis.

### 4.3.2 Increase in product value

Comparing the quality and value of the products in the different proposed project alternatives can pose problems. $CO_2$ in itself is of low 'energetic' and economic value. With the addition of other materials and conversion, more valuable products can be created but this limits the possibilities for proper comparison. The addition of materials and the conversion also have the largest impact on the added value. To properly compare these products, standardization will be used. The standardization will be based on how much of the product, in a certain project alternative, can be made with 1 ton of captured $CO_2$. By using this process, a project alternative that has $CO_2$ as output can be compared to alternatives in which a conversion of $CO_2$ takes place and therefore has another output. The economic value of these products will be estimated using available information about the prices of similar products. This provides a product value for a certain project alternative that can be compared with the base product, $CO_2$.

### 4.3.3 Regionality

Regionality is important for Meerlanden to increase social impact and sustainability as mentioned before. Local waste biomass is used for the generation of heat and offers potential for the capture of $CO_2$. Meerlanden is active in the region around Rijsenhout and working with the shareholding municipalities towards a circular economy. Finding demand for $CO_2$ based products that can be used in the region itself is thereby preferred. A criterion that measures the regionality of a project alternative is required to score the alternatives on regionality. The scoring will be based on the location of the end-user of the product. Table 5 shows the scoring that will be used to differentiate between the regionality of different project alternatives.

*Table 5: Regionality score overview*

| The location of the end-user of the product | Score |
|---|---|
| Meerlanden | 5 |
| Shareholding municipality | 4 |
| Serviced municipality | 3 |
| Netherlands | 2 |
| Outside the Netherlands | 1 |

The scoring for regionality is straightforward but an effective way to compare different project alternatives for their regionality potential. The highest score, 5, is given to project alternatives that can create products that will be used by Meerlanden. This leads to the highest regionality impact as no transport will be required. Waste biomass gathered by Meerlanden will lead, via heat and carbon capture, to a new product that Meerlanden can also use. If stakeholding municipalities can use the products in a certain project alternative, the regionality score will be a bit lower (4). The whole process if such a project alternative will still be focused on regionality but will be less that use by Meerlanden. The further a product finds its user from Meerlanden, the lower the regionality scoring with the lowest (1) given to project alternatives that can create products that can not be used in the Netherlands. In the MCA, the regionality score will be normalized to a value between 0 and 1 to give the final score.

### 4.3.4 The complexity of the production process

The complexity criterion of the production process follows from the conditions set by Meerlanden. Small biomass plants are most often found at relatively small companies that don't necessarily have to ability to deal with highly complex processes, which is also the case at Meerlanden. A highly complex production process could be done but would require a significant change in the companies operations. Less complexity will therefore be preferred to increase the feasibility of carbon utilization at small biomass plants. To determine the complexity of the production process, the complexity index is used.

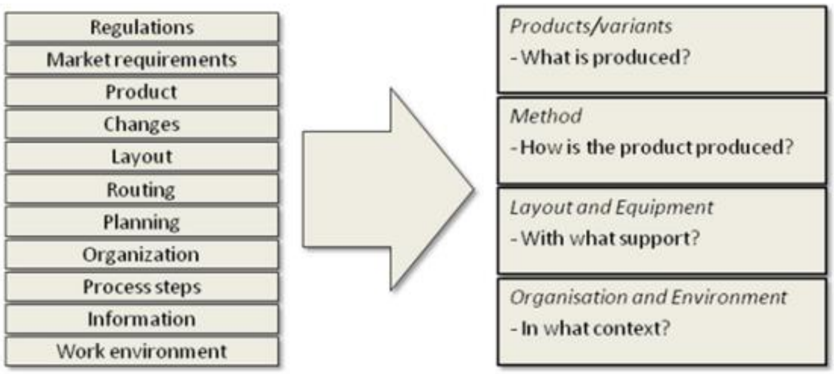


*Figure 9: Different aspects of production process complexity (Mattsson et al., 2011)*

Figure 9 shows the different aspects of the production process that influence the complexity. All these aspects can be summarised in four questions. The scoring of these four questions together determines the final complexity of the production process. Mattson *et al.* (2011) describe this process to estimate the complexity of existing or novel production processes. Table 6 shows the scale of the complexity score that is used in their method. The complexity index goes from no complexity to extensive complexity and is scaled accordingly.

*Table 6: Scale of complexity scoring (Mattsson et al., 2011)*

| Complexity indication | Complexity Index |
|---|---|
| No complexity | 0 |
| Minor complexity | 1 |
| Medium complexity | 3 |
| Extensive complexity | 9 |

To score alternatives for production process complexity, different aspects need to be considered. Even though the complexity parameters are designed for existing installations, it can give an estimation of complexity for novel installations. With the different levels of complexity, the estimation can be made for the proposed installations at Meerlanden. Based on the information gathered about the production processes in the project alternatives, the complexity score is estimated.

### 4.3.5 Long-term Carbon storage capability

Supplying $CO_2$ directly to greenhouses to be used as a plant growth stimulant limits the necessity for natural gas burning at those greenhouses and thereby helps in mitigating further $CO_2$ emissions. The downside of this process is that the maximum amount of $CO_2$ stored in the plants is 50% in the best possible scenario, with more realistic figures of 25% stored (Mikunda *et al.,* 2015). Besides the fact that most $CO_2$ goes directly back into the atmosphere, storing $CO_2$ in plants is a short term carbon storage method. As this is the reference alternative, project alternatives that offer long-term carbon storage potential are valued higher by Meerlanden. Seeking project alternatives that have long-term carbon storage capabilities is therefore desired. This criterion will be used to indicate if a project alternative has the potential to store carbon for a longer period and thereby increases its positive environmental impact.

### 4.3.6 Technology Readiness Level (TRL)

Of the shelve projects are not readily available for carbon utilization at this moment but there are big differences in technology readiness level between different proposed utilization options. Meerlanden prefers more proven technology and is not looking for pilot installations. The technology readiness level is the criterion that will be used to determine how proven the technology and proposed installations are.

| Phase | TRL | Hardware | Software |
|---|---|---|---|
| Research | 1 | Basic principles | |
| | 2 | Concept and application formulation | |
| | 3 | Concept validation | |
| Development | 4 | Experimental pilot | |
| | 5 | Demonstration pilot | |
| | 6 | Industrial pilot | |
| Deployment | 7 | First implementation | Industrialization detailed scope |
| | 8 | A few records of implementation | Release version |
| | 9 | Extensive implementation | |

*Figure 10: The Technology Readiness Levels (Blanc et al., 2017)*

The Technology Readiness Levels (Blanc *et al*., 2017). Figure 10 shows the different levels of readiness for technology as determined by Blanc *et al* (2017). It will be used to determine the TRL of the proposed project alternatives. The first important distinction is between the phases of research, development, and deployment. Meerlanden is seeking project alternatives in the deployment phase or late in the development phase (industrial pilot).

## 4.4 Carbon utilization alternatives

A selection of project alternatives is made based on the literature review. The selected project alternatives for the MCA with a short description are shown below in table 7. Appendix C shows the complete description and scoring of the project alternatives.

*Table 7: Project alternatives*

| Project alternative | Description |
|---|---|
| Methanol | Emissions-to-Liquids technology makes it possible to convert $CO_2$ to Methanol by using hydrogen (Carbon recycling, 2020). Depending on the installation, this can either be done by direct hydrogenation of $CO_2$ or hydrogenation of CO. Methanol can be blended with gasoline to create a more sustainable fuel for road transportation. |
| Ethanol | The electrochemical process makes it possible to create Ethanol from $CO_2$. Syngas is created from hydrogen and $CO_2$, which then gets converted into Ethanol. The direct electrochemical Ethanol production is less developed than Methanol production but progress is being made. The produced Ethanol can be used for road transportation or other applications. |
| Kerosene | Biokerosene is already being produced but the electrochemical production process is relatively new. It uses the same process as the Ethanol production via the syngas method. This will allow the production of more sustainable kerosene to be used at Schiphol. |
| Formic acid | Direct electrochemical conversion of $CO_2$ to formic acid is also being developed (VoltaChem, 2020). This would allow the captured $CO_2$ to be converted to formic acid which has a range of possible applications. Either the agricultural sector or the use as a hydrogen carrier is the most likely application for formic acid. |
| Compensatiesteen | The Compensatiesteen is based on the carbonatation process that is found in nature. It uses $CO_2$ instead of heat to create sand-limestone bricks suitable for construction. Sand, granulates, and an additive are bound by $CO_2$ into sand-limestone. In this process, 250 kg $CO_2$ is bound in every $m^3$ of Compensatiesteen. This allows for compensation of $CO_2$ emissions during construction which is stored in the bricks. |
| Food industry | The food industry uses $CO_2$ for a range of foods and beverages. Mainly soft drinks production has a large demand for $CO_2$. The traditional source of this $CO_2$ is from ethanol and ammonia production. Food grade $CO_2$ from a small biomass plant would add another stable source. |
| Textile industry | The use of $CO_2$ in the textile industry is relatively new. The main focus of this process is to limit the usage of water that is traditionally used with the washing of textiles. Coloring of textiles by using $CO_2$ not only limits the usage of water but also the impact on the environment with limited pollutants. Other stakeholders will be required to make necessary investments in installations that use $CO_2$ as the main method for washing of coloring textiles. |

The project alternatives are based on the literature review, expert opinion, and potential demand. The MCA will show which of the project alternatives will be best suited for further analysis.

## 4.5 Multi-criteria analysis of project alternatives

Table 8 shows all the results for the different proposed carbon utilization project alternatives. It becomes clear that kerosene production is the most expensive project alternative. Additional conversion steps, new processes, and expensive equipment all add up to the most expensive option. The most affordable alternative will be $CO_2$ capture for the textile industry. Compressing is required but the quality of $CO_2$ captured by the carbon capture installation will be high enough. This means that further purification will not be required which results in relatively low investment costs.

Formic acid is the simplest carboxylic acid and with a relatively low carbon content compared to other proposed alternatives, leads to high production amounts of formic acid. Formic acid is mainly used in the agricultural industry. If formic acid is used as a fuel (in the form of a hydrogen carrier), formic acid has a relatively high price compared to conventional 'fuel' types (methanol, ethanol, etc). The lowest value of $CO_2$ will be with the food and textile industry. As compression is required for adding the captured $CO_2$ to the OCAP network, costs are involved. This leads to a higher price of $CO_2$ compared to $CO_2$ directly from the capture installation at a lower pressure (Mikunda *et al.,* 2015).

Methanol and Ethanol score the highest in terms of regionality because the products can almost be directly used by Meerlanden. Stakeholding municipalities can also use these products to lower $CO_2$ emissions from transportation in the region. The food industry has the lowest score for regionality. Large food-grade $CO_2$ users are located elsewhere in the Netherlands which leads to are a relatively low score.

Processes that require less intervention will be less complex. This leads to the food and textile industry being less complex as they both only require to be compressed to be used in the designated industries. Kerosene production uses the most complex production process with the most steps, the expectation is therefore that this will be the most complex alternative.

Long-term carbon storage is only possible with Compensatiesteen production. The chemical binding between the other materials and the $CO_2$ leads to long term storage. $CO_2$ is stored for at least the lifetime of the construction in which it is used (Ruwbouwgroep, n.d.).

Formic acid and kerosene production directly from $CO_2$ both are the most recent possibilities for carbon utilization. These technologies are still being developed and not yet implemented in large scale installations. The TRL is therefore relatively low at 5. Ethanol and methanol are already produced in small quantities from $CO_2$ which therefore gives a higher TRL (Carbon recycling, 2020; Zeton, 2019). Both the food and textile industry have the highest TRL. Compressed $CO_2$ is already used in large quantities in a range of production processes, like the food and beverage industry. Equipment that uses compressed $CO_2$ for the textile industry is relatively new but this is not the case for the compressed $CO_2$ part of the process.

*Table 8: Overview of scores carbon utilization alternatives*

| | Methanol | Ethanol | Kerosene | Formic acid | Compensatie steen | Food industry | Textile industry |
|---|---|---|---|---|---|---|---|
| Investment costs (per ton) | €900 - €1100 | €1250 - €1875 | €3000 - €4000 | €1600 - €2500 | €1000 - €2000 | €73 - €146 | €73 - €96 |
| Change in product value (per ton) | €275 (€200 - €350) | €475 (€400 - €550) | €130 (€100 - €160) | €975 (€900 - €1050) | €650 (€500 - €800) | €115 (€80 - €150) | €115 (€80 - €150) |
| Regionality | 4,5 | 4,5 | 4 | 4 | 4 | 2 | 4 |
| Complexity | 6 | 5 | 7 | 6 | 3 | 1,5 | 1 |
| Carbon storage | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| TRL | 7 | 6 | 5 | 5 | 7 | 9 | 9 |

## 4.6 Analytic hierarchy process

Criteria selection is based on literature and expert opinion. Even though all criteria are important, they carry different weights in the MCA. Determining the weights is based on an Analytic hierarchy process. This makes it possible to weigh the criteria pair-wise and determine the ultimate weights to score the project alternatives.

The weights follow from the questionnaire done with Diederik Notenboom, the advisor of Meerlanden. Based on the information available about the different project alternatives and their impact on Meerlanden, a small questionnaire has been conducted. This questionnaire is shown in appendix D, in Dutch. The results from the questionnaire are shown below, in table 9.

*Table 9: results of questionnaire AHP*

| Criteria | Investment costs | Value | Regionality | Complexity | $CO_2$ storage | TLR | Sum | Percentage |
|---|---|---|---|---|---|---|---|---|
| Investment costs | 1 | 1/7 | 1/3 | 1 | 1/5 | 1/9 | 2,79 | 4% |
| Change in product value | 7 | 1 | 3 | 7 | 5 | 3 | 26 | 34% |
| Regionality | 3 | 1/3 | 1 | 7 | 1 | 1/3 | 12,67 | 17% |
| Complexity | 1 | 1/7 | 1/7 | 1 | 1/3 | 1/3 | 2,95 | 4% |
| $CO_2$ storage | 5 | 1/5 | 1 | 3 | 1 | 5 | 15,2 | 20% |
| TLR | 9 | 1/3 | 3 | 3 | 1/5 | 1 | 16,53 | 22% |
| Total | | | | | | | 76,14 | 1 |

As mentioned before, the criteria are weighted pair-wise. This means that when comparing two of the same criteria (investment costs -> investment costs, etc), they have equal importance. As described in section 2.3.1, a score of 7 means that value has very strong importance over investment costs. When comparing investment costs to value, the value still has very strong importance over investment costs but the effect is the opposite (investment costs -> value instead of value -> investment costs). 15 pair-wise comparisons were needed to weigh all the criteria against each other. Along with each criterion (horizontally), the scores are added up (column Sum). By dividing these criteria score by the total sum of all criteria, the percentage of each criterion is calculated (column percentage). This percentage is the weight that each criterion has for the MCA. The weights are shown separately in table 10.

*Table 10: Weights of criteria following from the AHP*

| Criteria | Weight |
|---|---|
| Investment costs | 4% |
| Change in product value | 34% |
| Regionality | 17% |
| Complexity | 4% |
| Carbon storage | 20% |
| Technology readiness level | 22% |

Investment costs and complexity of the production process have the lowest weights. For investment costs, if a business case can be made that has a positive social impact that will be sufficient to acquire the funds needed for the installation. This has to do with municipalities being the shareholders of Meerlanden which allows them to reach other ways of financing. The other low score weight, the complexity of the production process, has to do with the proposed alternatives. As Meerlanden is producing green gas, which requires different types of conversion and cleaning, the proposed alternatives do not seem to be much more complicated than what they are already used to doing. Under these circumstances and alternatives, complexity does not play a large role in the selection of alternatives.

The highest scoring criterion is the value of the product. This weighted score is relatively high because of the impact that it can have on the overall business case. Higher valued products often also mean products of higher quality. The utility of these products will therefore also be higher compared to other alternatives. This all leads to a relatively large impact on the value of the product for the scoring of the alternatives.

## 4.7 Selection of alternatives

The combination of the MCA with the AHP results in the final scoring of the project alternatives. Criteria that did not have a normalized score yet (values between 0 and 1) are normalized to conduct a proper scoring. The scores per criterion are corrected for the weight of that criterion and summed along the project alternative to generate the total score of that project alternative. Table 11 shows the final scores of the project alternatives.

*Table 11: Weighted MCA*

| | **Weight** | Methanol | Ethanol | Kerosene | Formic acid | Compensatiesteen | Food industry | Textile industry |
|---|---|---|---|---|---|---|---|---|
| Investment costs | 0,04 | 0,732 | 0,567 | 0 | 0,425 | 0,732 | 0,993 | 1 |
| Change in product value | 0,34 | 0,186 | 0,415 | 0,017 | 1 | 0,622 | 0 | 0 |
| Regionality | 0,17 | 1 | 1 | 0,8 | 0,8 | 0,8 | 0 | 0,8 |
| Complexity | 0,04 | 0,167 | 0,333 | 0 | 0,167 | 0,667 | 0,917 | 1 |
| Carbon storage | 0,20 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| TRL | 0,22 | 0,5 | 0,25 | 0 | 0 | 0,5 | 1 | 1 |
| **Score** | | 0,37 | 0,4 | 0,14 | 0,5 | 0,71 | 0,29 | 0,43 |

Methanol, Ethanol, and Kerosene project alternatives do not get selected for further analysis. They have relatively low scores and offer additional barriers for companies like Meerlanden. Mainly their change in product value is relatively low. These products would need to compete with traditional produced Methanol, Ethanol, and Kerosene. The potential added value is just too low to ensure a high enough score.

The food industry and textile industry both score well on complexity. The low change in product value and regionality lead to a low score for the food industry. Scoring for the textile industry could be described as high enough to be taken further into the analysis but this project alternative has a major disadvantage. Producing $CO_2$ for, if possible, the food industry ensures a large range of potential buyers with sufficient demand. The use of $CO_2$ in the textile industry is relatively new and not widely used in the Netherlands. This would mean that potential buyers need to invest in their facilities to make it a possibility for Meerlanden. Meerlanden would be dependent on these stakeholders to ensure that there is a market for such supply. This would severely impact the feasibility of investment into carbon capture and utilization installation for the textile industry.

The Compensatiesteen project alternative has the highest score and is followed by the formic acid production project alternative. The long term carbon storage potential of the Compensatiesteen project alternative is one of the main reasons for the relatively high score. This additional benefit, that the other project alternatives do not have, has a significant impact on the total score. Formic acid production is significantly more complex than the Compensatiesteen project alternative has high potential in terms of production. Both these project alternatives will be further analyzed with the use of the proposed SCBA and FCBA to offer financial implications.

# 5. Analysis setup

Chapter 5 describes the base setup for the cost-benefit analysis of the project alternatives for Meerlanden. Determined effects can be used in both the FCBA and the SCBA. Section 5.1 will provide insight into the problem analysis and the reference alternative. Section 5.2 explains the effects involved with the different alternatives and section 5.3 will explain the different costs. Variants and uncertainties are of great influence on a cost-benefit analysis and this analysis will deal with the uncertainties involved. Section 5.4 describes the used analysis. This setup will be used for both the financial cost-benefit analysis (chapter 6) and the social cost-benefit analysis (chapter 7).

## 5.1 Problem analysis

The problem analysis for the cost-benefit analysis is based on the main problem of the overall research. Meerlanden has plans to built a biomass plant and has the desire to capture the $CO_2$ to limit its environmental impact. The proposed utilization method of the captured $CO_2$ is supplying it to greenhouses. This decreases the demand for natural gas that is traditionally used to supply the $CO_2$ and will thereby have a positive impact on $CO_2$ emissions. The drawback of supplying $CO_2$ to greenhouses is the low uptake of $CO_2$ by plants, as 50% of the $CO_2$ immediately goes back into the atmosphere (Mikunda *et al., 2015)*.

The biomass plant combined with carbon capture and utilization is the main part of the proposed plans. Chapter 4 describes the MCA that has been conducted to offer the most promising project alternatives for Meerlanden. This is the major part of the problem analysis. The cost-benefit analysis will go deeper into the selected project alternatives to find the financial estimation for the two proposed project alternatives when they are compared to the reference alternative.

### 5.1.1 Definition reference alternative

The construction of the biomass plant is planned for 2021 and after construction, will be operating for 20 years (Meerlanden, 2020). The heat will be supplied to the regional heat network and the $CO_2$ will be captured and supplied to the OCAP network. Via the OCAP network, $CO_2$ will be delivered to greenhouses to be used as a plant stimulant. Figure 11 shows the simplified overview of the process in the reference alternative.

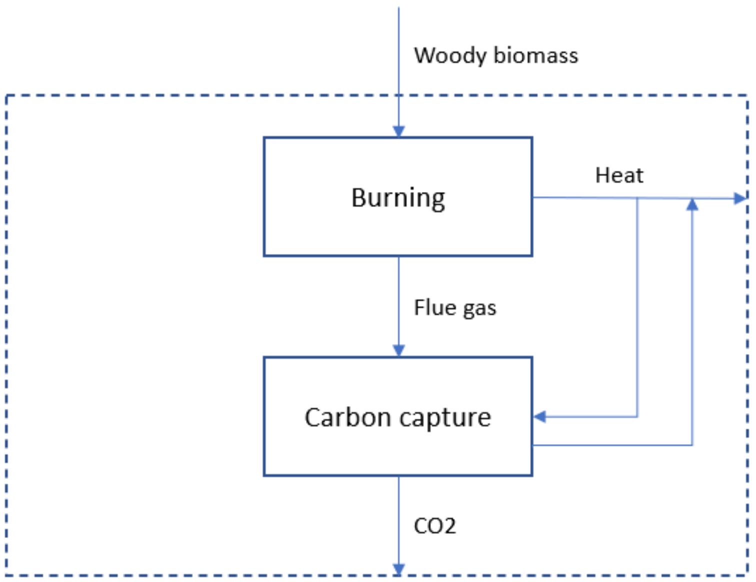


*Figure 11: Reference alternative*

The woody biomass is collected by Meerlanden and dried (Meerlanden, 2020). Burning the woody biomass will provide both heat and $CO_2$ as products that will be used and sold. Additionally, the $CO_2$ from the biomass plant is not the only source. When the biomass plant is implemented, this also allows the use of an additional 3000 ton of $CO_2$ from the green gas installation already located at Meerlanden (Meerlanden, 2020). Without the biomass plant, this $CO_2$ (which is removed from biogas to create green gas) can not be utilized as the supply is not sufficient to justify a connection to the OCAP network. With the additional 7000 tons from the carbon capture installation and the total supply of 10000 tons of $CO_2$ per year, this would justify the construction of the connection to the OCAP network.

### 5.1.2 Definition project alternatives

The SCBA will cover two project alternatives that followed from the MCA conducted in chapter 4. Both of these project alternatives will be further defined in the upcoming sections.

#### *5.1.2.1 Project alternative 1: Compensatiesteen*

As mentioned in the previous chapter, the Compensatiesteen project alternative involves the synthetic carbonatation of sand-limestone. By using sand, granulates from the steel industry, and binding agent bricks are formed. Traditionally these bricks are hardened by using heat which leads to significant $CO_2$ emissions during the process. The binding agent in the Compensatiesteen production process makes it possible to harden the bricks with $CO_2$. This process takes place under pressure and the chemical hardening stores 250 kg $CO_2$ for every $m^3$ of Compensatiesteen (Ruwbouwgroep, n.d.). The process thereby allows compensating a part of the $CO_2$ emissions involved in the construction of houses. The simplified figure 12 shows the schematic production process of Compensatiesteen.

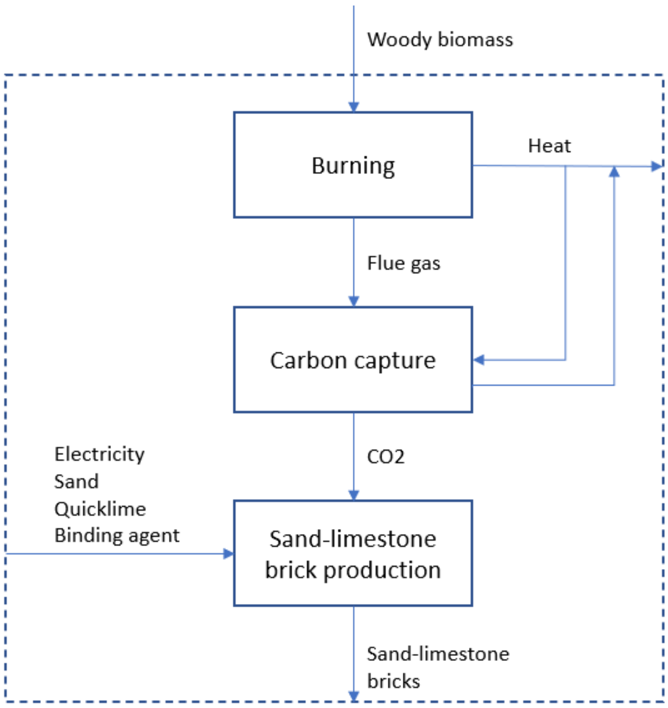


*Figure 12: Flowchart of project alternative Compensatiesteen*

The Compensatiesteen alternative is an addition to the reference alternative. The carbon capture installation ensures a large enough supply of $CO_2$ for a facility. Sand, quicklime, and the binding agent will be transported to Meerlanden. Besides these raw materials, electricity is required for the process. In the factory, the bricks will be pressed and hardened using the captured and stored $CO_2$ from the biomass plant. The bricks can then be sold to retailers, contractors, or used to build the planned housing close to Rijsenhout.

The carbon capture at the biomass plant and the available $CO_2$ from the green gas installation can together supply 10000 tons of $CO_2$ per year (Meerlanden, 2020). With 250 kg $CO_2$/m3 Compensatiesteen, 40000 m3 limestone bricks (Compensatiesteen) can be produced (Ruwbouwgroep, n.d.). This will be sufficient limestone brick for around 2000 houses at 20 $m^3$ per house (Ruwbouw groep, n.d.). The weight of Compensatiesteen is 1950 kg/$m^3$ and with 250 kg/$m^3$ $CO_2$ combined during the production process, which means 1700 kg/m3 sand, quicklime, and the binding agent.

At least 60% of raw materials are recycled and upgraded residuals from the steel industry (Ruwbouwgroep, n.d.). As precise information is unavailable, the assumption is therefore that the Compensatiesteen production process follows the ratios for traditional production. 90-95% sand, 4-10% quicklime, and 1% water is the traditional ratio for sand-limestone (VNK, 2018). During traditional sand-limestone brick construction, the 'binding agent' is the water that gets removed with the use of heat. The assumption is made that the water gets replaced by the binding agent that ensures the hardening process by using $CO_2$. By using these assumptions, the following figures are found and table 12 shows the effect of these assumptions.

*Table 12: Overview of raw materials for Compensatiesteen*

| Material | 1 m3 Compensatiesteen | 40000 m3 Compensatiesteen |
|---|---|---|
| Quicklime | 153 kg | 6120 ton |
| Sand | 1530 kg | 61200 ton |
| Binding agent | 17 kg | 680 ton |
| $CO_2$ | 250 kg | 10000 ton |

These assumptions will be used to calculate the different benefits and costs in the SCBA. These assumptions will introduce additional uncertainty in this project alternative. As mentioned before, the Compensatiesteen production process is patented and the Ruwbouw group is not transparent about this process. If with the made assumptions, Compensatiesteen would be feasible, cooperation with the Ruwbouw groep will be required to implement such a production facility at Meerlanden.

#### *5.1.2.2 Project alternative 2: Formic acid*

The other project alternative involves the electrochemical production of formic acid. Formic acid has a range of applications and is traditionally produced from fossil sources. With the electrochemical conversion, the $CO_2$ captured at the biomass plant will be converted into formic acid. Again, the first part of the production process is the same as the reference alternative. The biomass plant has the same capacity and the same output. By combining the $CO_2$ with hydrogen produced from water, formic acid can be formed in the reaction chamber. Figure 13 shows a simplified schematic of the production process.

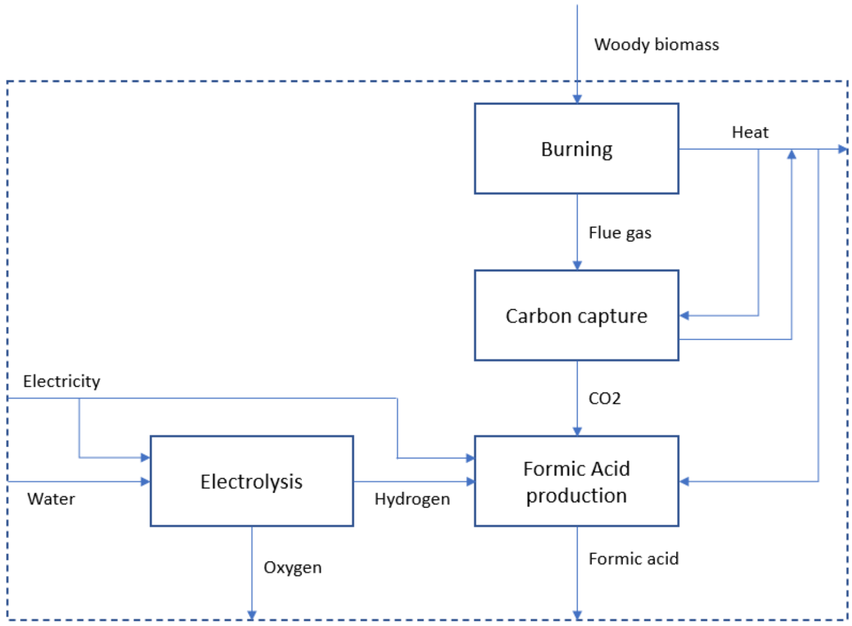


*Figure 13: Flowchart of the LCA model Formic acid production*

10000 tons of $CO_2$ is again available for the forming of formic acid. According to Pérez-Fortes & Tzimas (2016), 12000 tons of formic can be produced. One of the biggest issues when using the electrochemical process to produce formic acid is the high electricity demand. Electricity consumption of 4,054 MWh/ton FA (Pérez-Fortes & Tzimas, 2016) is required. Besides the high electricity requirements, steam or heat are also required in the process. This can be supplied by the biomass plant.

The main downside of this project alternative is the requirement for a large electrolyzer. As Pérez-Fortes & Tzimas (2016) describe, this size electrolyzer does not exist yet. This is an additional limitation for the implementation of the formic acid facility at Meerlanden. The most desirable outcome would be for Meerlanden to use formic acid as a hydrogen carrier to ensure the possibility of zero-emission heavy transport. This technology is also not ready yet but is well underway (Dens, 2020). These facts will introduce additional uncertainty to the project alternative but it does not limit the future potential.

## 5.2 Identification of project effects

Project effects are directly associated with the project alternatives and are used to evaluate the difference between the reference alternative and the implementation of the proposed projects. The project effects in table 13 will be used to evaluate these differences during this study.

*Table 13: Overview of relevant project effects*

| Project effect | Definition | Direct or indirect effects? | Affected parties |
|---|---|---|---|
| Change in investment costs | The additional investment required to realize the project | Direct | Meerlanden / shareholders |
| Change in operating costs | The additional operating costs associated with the project | Direct | Meerlanden |
| Change in product revenue | The additional revenue because of added value | Direct | Meerlanden |
| Environmental effects | The change in environmental costs (i.e. noise pollution, $CO_2$ emission, and air pollution) | Direct / indirect | Society |

This study assumes that the most relevant effects caused by the two project alternatives will be: a) change in investment costs; b) change in operating costs; c) change in product revenue; and d) environmental effects. Table 13 also shows the definitions for the project effects and indicates if they are either a direct or indirect effect. Furthermore, it also highlights the most relevant parties affected by the implementation of the projects.

### 5.2.1 Direct effects

The direct effects will be further specified in this section. Additionally, valuations for the different project effects will be explained.

#### *5.2.1.1 Change in investment costs*

The biomass plant is the basis for the reference alternative and the two project alternatives. Without this facility, there will be no $CO_2$ to be captured and utilized. Investment costs for the reference alternative therefore consist of the cost for carbon capture and delivery to greenhouses. According to Frames B.V. and Meerlanden, these costs are put at 3,35 million euros (Frames, 2020; Meerlanden, 2020). This is the base cost of CCU at Meerlanden. The change in investment costs is the cost of the extended facility. The carbon capture installation is identical in both the project alternatives but the utilization facility will be different.

The compensatiesteen project alternative requires additional investment compared to the reference alternative. The facility itself, the machinery, and groundwork all require an additional investment. The expert from the Ruwbouw groep, Frens Timmermans, has highlighted that the costs for such a facility would “be in the millions”. To further specify the costs, a more traditional sand-limestone facility is used as a reference for the investment costs. Rewin had plans to built a sand-limestone factory in 2006. The investment costs associated with that facility based on traditional production was 20 million euros (NV REWIN West-Brabant, 2006). The proposed facility at Meerlanden has a yearly sand-limestone production capacity for around 2000 houses and the Rewin had a base capacity for 5000 houses (NV REWIN West-Brabant, 2006). This production capacity is used to scale the investment costs for the Compensatiesteen project alternative. Scaling based on this production capacity gives a base investment cost of 8 million euros. When assuming more costs are involved with a non-traditional facility, the assumption is made that investment costs could be around 50% higher. This offers an investment costs range of between 8 million and 12 million euros.

The formic acid project alternative also has a significant change in investment costs. The installation itself is not as large as the Compensatiesteen but the technology is more complex and expensive. Electrolysis is the main part of the electrochemical production of formic acid. This technology is expensive as it requires rare minerals and, as mentioned before, is quite complex. Pérez-Fortes & Tzimas (2016) provide an estimation of the cost of formic acid production. In their report, the processed amount of similar is identical to the amount Meerlanden will be able to provide (10.000 tons). Their estimation is 16 million euros for such a facility. Installing a similar installation at Meerlanden gives no guarantee that the investment costs will also be similar. Therefore, the assumption is made that investment costs can be significantly higher. This is done in the same way as for the other project alternative and provides an investment cost range of between 16 and 25 million euros. Table 14 shows the total investment cost and the change in investment costs.

*Table 14: Overview of the change in investment cost*

| | Reference alternative | Compensatiesteen | Formic acid |
|---|---|---|---|
| Investment cost | €3.250.000 | €11.250.000 - €15.250.000 | €19.250.000 - €28.250.000 |
| Change in investment cost | - | €8.000.000 - €12.000.000 | €16.000.000 - €25.000.000 |

### *5.2.1.2 Change in operating costs*

Both the reference alternative and project alternatives have to deal with operating costs. The operating costs are all the costs associated with production. As the project alternatives use the $CO_2$ produced in the reference alternative, there can be a significant change in operating costs. First, the operating costs of the reference alternative are estimated. Frames B.V. has provided information about the operational costs of the carbon capture installation. The main impact of the carbon capture installation on the biomass plant is the demand for heat. With the specifications from Frames (2020), the carbon capture installation has a demand of 3,5 MWth. This means that one of the two boilers in the biomass plant needs to be dedicated to the carbon capture installation. 90% of this heat used during the carbon capture process can be recovered in the form of water with a temperature above 70 degrees (Frames, 2020). This temperature would be sufficient for the heat network and thereby limits the loss of heat to the heat network to 5% of the produced yearly amount. Meerlanden prices the produced heat at €0,036 per kWh (thermal) and determined that the total production of the biomass plant would involve 39780 MWh (thermal) per year.

As the facility is designed for a certain amount of heat, the required biomass needs to be increased to correct for this loss in heat. The estimation is that increasing the supply of biomass by 10% will compensate for this heat loss. Furthermore, the capture of $CO_2$ requires 60 kWh per ton produced $CO_2$ (Frames, 2020). Besides heat and electricity, chemicals are required for the capture of $CO_2$. The process of Frames uses Galloxol, Glycol, and water which together will cost €1,32 per ton produced $CO_2$ (Frames, 2020). Frames does not offer additional information about operational costs, so estimations need to be made about maintenance, personnel, insurances, etc.

According to information from Meerlanden, the biomass facility has an investment cost of 3,5 million euros, which is similar to the investment costs of the carbon capture installation (Meerlanden, 2020). They estimated 460.000 euro of operation cost for the biomass plant. This included 35.000 euro of electricity costs which is calculated separately for the carbon capture installation. Therefore, we assume that the other costs for the carbon capture installation are 425.000 euros per year. The loss in heat revenue, the electricity price of €0,08 per kWh (Main Energie, 2020), and the other specified costs, the total yearly operational costs for the carbon capture installation are €550.000.

The operational costs for the Compensatiesteen alternative are more diverse. As the figure in section 5.1.2.1 shows and has been described before, raw materials are required for the production of sand-limestone bricks. These raw materials will be a significant part of the operational cost. The exact ratios, mentioned before, are not known but we will make an assumption based on information that we do know. Sand is the main raw material required for sand-limestone brick. Concrete sand is most likely used for the process, and including transportation, the price will be around €20 per ton for big orders (AVG, 2020). The quicklime is the secondary raw material required for the production process. The Ruwbouw group claims that at least 60% of the raw material will be sourced from upgraded material from the steel industry. This could be from Tata steel in Ijmuiden but it is still unclear which materials exactly will be from secondary sources. Estimations must be made for the price of quicklime because prices for large quantities are not public. Reference prices found are between €140 (Made-in-China, 2020) and €320 (De oplosmiddelspecialist, 2020) per ton. The higher reference price only sells in batches of 1 ton, it is likely prices for far larger quantities will be lower. The estimation will be that €200 per ton will be possible. Besides the sand and quicklime, the binding agent is the most important material. It is unclear which compound is used to bind the $CO_2$ into the sand-limestone brick and this makes it difficult to assume the exact ratios and price. The binding agent used and thereby also the price involved, are not available. Quicklime is 10 times more expensive than the sand used, so the assumption is made that the binding agent is 10 times more expensive than the quicklime. This means €2000 per ton of binding agent. Sensitivity analysis will be used to further analyze the effect of different binding agent prices. The referenced facility from Rewin employed 30 employees (Rewin, 2006), which means that for the proposed facility at Meerlanden 15 personnel will be required. Meerlanden calculated €75.000 in personnel costs for the biomass installation (Meerlanden, 2020) at 2 fte. For the Compensatiesteen facility, this would amount to €562500 per year. Other costs will be scaled to the other costs for the biomass plant without the personnel cost. The estimation for maintenance, electricity, guarantees, insurances, etc will be around €1.000.000 based on the reference costs from the biomass plant. The total yearly operating cost for the Compensatiesteen project alternative will be around €5.400.000.

The operating costs for the formic acid project alternative will be based on the study done by Pérez-Fortes & Tzimas (2016). Their study included salary and overheads, maintenance, interest, utilities, consumables, and raw materials. All these costs amount to a yearly operating cost of around €18.500.000. 12000 tons of formic acid can be produced per year. The average production will therefore be 1542 €/tFA (Pérez-Fortes & Tzimas, 2016). The overview of the total yearly operating cost and total yearly change in operating cost is shown in table 15.

*Table 15: Overview of yearly operating costs*

| | Reference alternative | Compensatiesteen | Formic acid |
|---|---|---|---|
| Operating cost | €575.000 | €5.950.000 | €19.050.000 |
| Change in operating cost | - | €5.375.000 | €18.475.000 |

### 5.2.1.3 Change in product revenue

Besides the operating cost, the product revenue will have a large effect on the feasibility of different alternatives. The reference alternative has a relatively straightforward valuation for product revenue. The carbon capture installation can produce 7000 tons of $CO_2$, and combined with the 3000 tons from the green gas facility, 10000 tons of $CO_2$ van be sold. $CO_2$ for greenhouses is valued between €50 and €80 per ton of $CO_2$ (Mikunda *et al.,* 2015). With the average price for $CO_2$, this amounts to €650.000.

The product revenue for Compensatiesteen is more complicated and requires further assumptions. According to the product specification from the Ruwbouw groep (n.d.), 40.000 $m^3$ is equal to 78000 tons of sand-limestone bricks. The thin layer mortar bricks are 100 mm wide, 168 mm high, and 437 mm long. This accounts for around 135 bricks per $m^3$ and 14 kg (1900/135) per brick. 40.000 $m^3$ and 135 bricks per $m^3$ are used to calculate the possible product revenue. The average price for sand-limestone bricks of the same size is around €1,50 (Bouwmaterialenkopen, 2020). This gives a product revenue of around €7.700.000. The change of product revenue is the difference between the reference alternative and the project alternative, which amounts to €7.050.000.

The reference price for formic acid is €650 per ton (Pérez-Fortest & Tzimas, 2016). The proposed facility can produce 12.000 tons of formic acid per year. This accounts for a product revenue of € 7.800.000

per year. Correcting this product for the revenue from the reference alternative gives the change in product revenue. This comes down to €7.150.000. Table 16 shows an overview of the product revenue and the change in product revenue.

*Table 16: Overview of product revenue*

| | Reference alternative | Compensatiesteen | Formic acid |
|---|---|---|---|
| Product revenue | €650.000 | €7.700.000 | €7.800.000 |
| Change in product revenue | - | €7.050.000 | €7.150.000 |

### 5.2.2 External effects

The biomass plant is built to find a useful purpose for the woody biomass Meerlanden has available. It is not a policy to increase air quality or limit $CO_2$ emissions, these are indirect effects of the implementation of the carbon capture installation. The main indirect effects of the Meerlanden case are the environmental effects. These effects will be further explained in section 5.2.2.1.

**Environmental effects**

The environmental effects are defined as the change in environmental costs which are caused by the implementation of the project. Three types of environmental costs will be included: a) climate change costs; b) noise costs; c) air pollution. These costs are not only for Meerlanden but also for society as a whole.

a) Climate change costs

Climate change costs are mainly caused by the emission of greenhouse gases ($CO_2$, $CH_4$, etc). They impact society by the increase in human health costs, sea-level rise, extreme weather, and damage to ecosystems. Both the reference alternative and project alternative will try to decrease the climate change costs in total. The reference alternative, delivering $CO_2$ to greenhouses, has a net 0,91 ton $CO_2$ reduction for every ton of external delivered $CO_2$ (Ecorys, 2020). The value of $CO_2$ reduction does not have a consensus and there is a large difference between the value of $CO_2$ in the ETS and the valuation of $CO_2$ by different agencies like PBL. During the sensitivity analysis, different values for avoided $CO_2$ emissions will be tested but for the SCBA, the value for $CO_2$ from the ETS is used. Currently, in the ETS, $CO_2$ is valued at around €30 per ton emitted $CO_2$ (Ember climate, 2020).

The Compensatiesteen alternative decreases climate change costs by storing $CO_2$ in the produced bricks. This provides an immediate $CO_2$ reduction but does not include all the other activities involved with the production. The main contributor to the $CO_2$ emissions of Compensatiesteen will be the transport of the raw materials. At least 60% of the raw material can come from the steel industry, as stated by the Ruwbouw groep. The closest steel industry for Meerlanden is located in Ijmuiden, at Tata Steel with a distance to Meerlanden of 30 km. The assumption will be that 60% of raw materials will come from Ijmuiden and the other 40% will come from twice the distance (60km). 0,171 kg $CO_2$ / ton-km will be used to calculate the $CO_2$ emissions of this transport (Milieubarometer, 2020). The Compensatiesteen will be compared with standard sand-lime stone bricks to estimate the net $CO_2$ reduction. Calduran offers an insight into the $CO_2$ footprint of sand-limestone bricks (Calduran, 2012). From their $CO_2$ monitoring information can be concluded that 1 ton of sand-limestone brick has a $CO_2$ footprint of around 315 kg (68,11 gram $CO_2$ / bwf = 2,1610 kg brick == 1-ton lime-sandstone bricks = 315,18 kg $CO_2$ emissions)

For formic acid production, the avoided $CO_2$ emissions will have the largest impact. Traditional formic acid production, based on fossil fuels, has a significant $CO_2$ emission impact. By producing formic acid with renewable energy, the avoided $CO_2$ emissions are at 2.18 $tCO_2$/tFA (Pérez-Fortes & Tzimas, 2016). When sold, the formic acid needs to be transported which will increase the $CO_2$ emissions of the overall project. The assumption is made that produced $CO_2$ needs to be transported over an average distance of 100 km as formic acid is mainly used in the agricultural sector. Similar transport emissions are taken into account at 0,171 kg $CO_2$ / ton-km.

b) Noise pollution

Noise pollution can have a severe impact on society and residents living close to project locations. The main sources are sounds produced by vehicles and facilities. They can lead to annoyance and health costs in the long term. The reference alternative will give no additional noise, as the carbon capture installation has the same sound level as the biomass plant.

The compensatiesteen alternative will have a noise impact on the residents living close to Meerlanden. There is already a large amount of truck movement every day caused by waste management. Raw materials needed for the production will cause the number of truck movements to increase. With 35000 $m^3$ of material needed to be transported to Meerlanden, and with an average load potential per truck of 25 $m^3$, this means an additional 4 truck movements per day. The valuation will be based on a study by CE Delft (2008). They estimated the noise costs of freight transport at 0.05 euro/vehicle-km (CE Delft, 2008).

The formic acid facility is assumed to have similar noise levels compared to the biomass plants and therefore no additional noise costs. The product, the formic acid, needs to be transported to the costumers. This will increase the noise costs for the direct residents surrounding Meerlanden and society. The same estimate for the noise costs of freight transport, 0,05 euro/vehicle-km (Maibach *et al.*, 2008), will be used. Tankers to carry fuel or other chemicals have an average capacity of 40 $m^3$. This leads to only one, on average, daily truck movement with thereby limited noise costs.

c) Air pollution

Air pollution costs are caused by the emission of air pollutants. Air pollutants are mainly particulate matter, NOx, $SO_2$, VOC, etc, and have an impact on the health costs of society. Besides health costs, building and material damages, crop losses in agriculture, and impacts on biodiversity also play a role in air pollution costs (Maibach *et al.,* 2008). The carbon capture installation will not increase air pollution. Heavy transport is one of the main emitters of these air pollutants when looking at the proposed project alternatives.

Transport is assumed to be the main source of air pollution in the Compensatiesteen alternative. The additional heavy transport required for the raw material will have an impact on air pollution. 4 truck movements per day will be required to supply the raw material necessary for production. CE Delft (2008) has evaluated the air pollution costs for heavy transport vehicles. Transport of raw material for Compensatiesteen production will mainly take place along motorways. The valuation of air pollution on motorways for heavy trucks is put at 0,028 euro/vehicle-km (Maibach *et al.,* 2008).

Formic acid production will not cause air pollution. Transport of the product, the formic acid, will affect air pollution. The same valuation by CE Delft will be used to value the distance over which the formic acid is transported. As transport is assumed to take place along motorways, the valuation is the same with 0,028 euro/vehicle-km (Maibach *et al.,* 2008).

Table 17 shows an overview of the environmental effects of the project alternatives.

*Table 17: Overview of environmental effects*

| | Reference alternative | Compensatiesteen | Formic acid |
|---|---|---|---|
| Environmental benefit | € 273.000,00 | €737.521,20 | € 784.800,00 |
| Environmental cost | €0 | -€ 19.221,30 | -€ 8.496,00 |
| Change in environmental effects | - | € 445.299,42 | € 503.304,00 |

### 5.2.2 Overview effects

When combining all the effects of the cost-benefit analyses, the following table 18 can be constructed. The investment costs are one time and the other costs will recurring yearly. It becomes clear that, without discounting or correcting for the lifetime of the facilities, the reference and Compensatiesteen alternative have the potential to generate a profit. Both their product revenue is estimated higher than their operating cost which could lead to a profitable installation. The formic acid alternative is estimated to have a far higher operating cost than product revenue. This can lead to issues when conducting the cost-benefit analysis as it is unlikely that such a facility can generate a profit. The FCBA and SCBA in chapters 6 and 7 will finally determine the net present value of the project alternatives and the feasibility of such facilities for Meerlanden.

*Table 18: Project effects (In million euro)*

| Project effects | Alternative | Reference (greenhouses) | Compensatiesteen | Formic acid |
|---|---|---|---|---|
| **Investment costs** | | **-€ 3,4** | **-€ 13,4** | **-€ 23,9** |
| **Operating costs** | | **-€ 0,6** | **-€ 5,4** | **-€ 18,5** |
| **Product revenue** | | **€ 0,7** | **€ 6,5** | **€ 7,8** |
| **Environmental effects** | | **€ 0,3** | **€0,7** | **€ 0,8** |

## 5.3 Variants and uncertainty analysis

CBA is an ex-ante evaluation of policy measures (Romijn & Renes, 2013). This means that before the implementation of projects the costs, effects, and benefits need to be estimated. In section 5.2, these are estimated and assumed. Besides these estimations, there is always a factor of uncertainty. Not until projects are operating and ex-post the final costs, effects and benefits can be assessed, there is always uncertainty about the estimations. Variant and uncertainty analysis will help in dealing with these uncertainties.

### 5.3.1 Variant analysis

The variant analysis will be used to deal with policy uncertainty and uncertainty about the future. The formic acid project alternative is based on the assumption that the produced formic acid is sold on the open market. This limits the indirect benefits of producing formic acid. Dens have already developed a formic acid engine that can power a city bus (TU Eindhoven, 2018). If they succeed to decrease the size and make the technology applicable to garbage trucks, Meerlanden can use this technology to further decrease their local environmental effects. To mitigate this uncertainty, a variant analysis will be conducted. It will divert from the project alternative in terms of investment costs and environmental effects. The green gas vehicles will be replaced by formic acid vehicles. Therefore, revenue does not change. Investing in such vehicles requires a significant investment but will have a positive environmental impact.

Meerlanden currently has 14 time-fill installations that allow heavy vehicles (like garbage trucks) to fill at night (PitPoint, 2018) with green gas. This limits the pressure on their green gas infrastructure. The preference is therefore to have at least the same amount of heavy-duty trucks using formic acid to limit the environmental effects in the urban environment. The existing garbage trucks have an estimated $CO_2$ emission of 1,1 kg/km (Milieubarometer, 2020). 100 km per working day will be assumed to estimate the environmental effects (Logistiek010, n.d.). Estimating costs for novel technology can be complex. Formic acid trucks are based on hydrogen technology. Essentially, the engine removes the hydrogen from the formic acid to generate electricity on which the vehicles run. Roland Berger (2017) assumes the average investment cost for a hydrogen fuel cell heavy-duty transport vehicle at €300.000. The formic acid installation essentially doubles the engine and therefore is assumed to also double the engine investment costs. Based on the report from Roland Berger (2017), the total cost should come down to €400.000 per vehicle. As a fuel cell/formic acid vehicle emits no harmful pollutants, this further reduces the local environmental impact. Besides the reduced emissions, fuel cell-based transport significantly reducing noise pollution. The waste collection takes place during the day which limits the noise impact of heavy vehicles. Because of the urban areas in which the waste is collected, the noise costs tend to be higher. These factors combined, the noise costs are estimated at 0,07 €/vkm (Maibach *et al.,* 2008). The formic acid fuel cell vehicles do not have these noise costs which makes it a positive impact. Table 19 shows the changes compared to the formic acid project alternative

*Table 19: Overview of changes compared to formic acid alternative*

| | Formic acid trucks |
|---|---|
| Additional investment costs | €5.600.000 |
| Additional environmental benefits | € 37.492,00 |

## 5.3.2 Uncertainty analysis

Uncertainty is inherently connected to a CBA. The estimations and valuations of project effects have therefore a limited predictive capability. To mitigate a part of this uncertainty, project effects are tested for sensitivity. This sensitivity analysis will show the robustness of the SCBA results. Several changes are made to the project effects to investigate the impact on the results. The following section will describe these changes.

### *5.3.2.1 $CO_2$ value*

The SCBA is set up with the current $CO_2$ value from the ETS. This value is relatively low at 30€/ton and is expected to rise in the future. The European Commission limits the issue of $CO_2$ emission rights every year which will impact the $CO_2$ value in the long term. 100€/ton $CO_2$ is the estimation for the price that it should have been in 2018 to keep the global temperature rise between 2 degrees (Bollen *et al.,* 2019). Therefore, the impact of this increase in $CO_2$ price will be used to test the results. An even higher increase of $CO_2$ price, 200€/ton, will also be used to test the sensitivity of the results. The changes that have been made are shown in table 20.

*Table 20: Changes made to $CO_2$ pricing*

| | $CO_2$ pricing (€/ton) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | €30 | €30 | €30 |
| Scenario with required $CO_2$ pricing | €100 | €100 | €100 |
| Scenario with higher $CO_2$ price | €200 | €200 | €200 |

### 5.3.2.2 Investment costs

The reference alternative has been provided with information about the required investment. No uncertainty is therefore involved in the reference alternative. This does not apply to the project alternatives. The Compensatiesteen alternative is based on a similar facility but with a different production method. The formic acid installation is based on a report that offers a general price estimation which increases the risks involved with that evaluation. Both project alternatives have an investment cost range from the MCA. These ranges will be used to test the sensitivity of the FCBA and SCBA for changes in investment costs. The changes that are made are shown in table 21.

*Table 21: Changes made to investment costs*

| | Investment costs (€) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | € 3.350.000 | €10.000.000 | €20.500.000 |
| Scenario with lower investment costs | € 3.350.000 | € 8.000.000 | €16.000.000 |
| Scenario with higher investment costs | € 3.350.000 | €12.000.000 | €25.000.000 |

### 5.3.2.3 Raw material prices

Compensatiesteen project alternative is heavily dependent on raw materials. Sand and quicklime are assumed to be required for the production process. Those prices are relatively stable in the current situation but can change in the future. This uncertainty needs to be acknowledged and tested to increase the robustness of the outcome. A 50% increase and a 50% decrease in prices are taken into account to evaluate the robustness. Table 22 shows the changes that are made.

*Table 22: Changes made to the raw material costs*

| | Raw material costs (€/ton) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | - | 100% | - |
| Scenario with lower raw material costs | - | 50% | - |
| Scenario with higher raw material costs | - | 150% | - |

### 5.3.2.4 Binding agent

The process of creating Compensatisteen is patented and not publicly available. 60% of the material can be from secondary sources (like the steel industry) and sand is the main raw material. Traditionally sand, quicklime, and a small amount of water create a chemical reaction under the influence of heat.

When the heat is replaced by $CO_2$, the chemical reaction needs to be supported by a binding agent. The binding that is used is also not publicly known, so estimations need to be made to test the sensitivity of the model. Assumed is that the binding agent is 10 times more expensive than the quicklime. To test the sensitivity of the SCBA, a 50% decrease, and a 50% increase in the estimated price are taken into account. Table 23 shows the changes made to the SCBA.

*Table 23: Small change made to binding agent cost*

| | Binding agent cost (€/ton) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | - | €2000 | - |
| Scenario with lower binding agent costs | - | €1000 | - |
| Scenario with higher binding agent costs | - | €3000 | - |

To better assess the impact of the binding agent cost on the social cost-benefit analysis, besides the small change, a large change will be taken into account. As the assumption is made that the binding agent can be 10 times more expensive than quicklime, a factor 10 difference could be possible. This leads to the following value that will be used. Table 24 shows these changes.

*Table 24: Large change made to binding agent cost*

| | Binding agent cost (€/ton) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | - | €2000 | - |
| Scenario with far lower binding agent costs | - | €200 | - |
| Scenario with far higher binding agent costs | - | €20000 | - |

### *5.3.2.5 Electricity price*

Electricity price plays a role in all the alternatives. Price changes will have the biggest impact on the formic acid alternative. For the production of formic acid, as it is used as a hydrogen carrier, hydrogen is required for the process. The hydrogen is produced with electrolysis which uses a large amount of electricity. Every ton of produced formic acid requires 4,054 MWh of electricity (Pérez-Fortes & Tzimas, 2016). With an average electricity price of €0,08 per kWh, this comes down to around €320 per ton formic acid. Changes in the electricity price will have a significant impact on the operating cost of this alternative. Besides the formic acid alternative, the carbon capture installation itself requires 60 kWh per ton captured $CO_2$ (Frames, 2020). When the value of $CO_2$ is low, changes in electricity prices can also have a significant impact. Furthermore, the Compensatiesteen alternative is also influenced by changes in the electricity price. Operating the facility will require electricity, especially for the pressurization part of the production process. Table 25 shows the changes made to the electricity price to test for robustness.

*Table 25: Changes made to electricity price*

| | Electricity price (€/kWh) | | |
|---|---|---|---|
| | Reference alternative | Compensatiesteen | Formic acid |
| Reference scenario | €0,08 | €0,08 | €0,08 |
| Scenario with lower electricity price | €0,04 | €0,04 | €0,04 |
| Scenario with higher electricity price | €0,12 | €0,12 | €0,12 |

# 6. Financial cost-benefit analysis

This chapter will continue about the financial consequences of carbon capture and utilization for Meerlanden. Even though Meerlanden and other companies strive to increase social welfare by implementing different measures in terms of biomass and carbon capture, they remain companies. Financial estimations will be based on the social cost-benefit analysis but without the environmental effects. These effects have a positive or negative effect on society but will not necessarily generate more revenue for Meerlanden or other companies. Section 6.1 will discuss the short term consequences and section 6.2 will discuss the long term consequences. Section 6.3 will give insight into the sensitivity analysis for the financial consequences and section 6.4 will highlight the conclusion about the financial implications for Meerlanden.

## 6.1 Short term financial consequences

The assumptions and estimations made in chapter 5 for the social cost-benefit analysis are used to estimate the financial consequences. As social effects can be monetized, they remain external effects. This means that increased social welfare or reduced environmental impact will not increase revenue for Meerlanden. Therefore, only direct effects are taking into account to access the financial consequences. As described in chapter 5, the direct effects are the investment costs, operating costs, and product revenue. Table 26 shows an overview of the financial consequences of Meerlanden.

*Table 26: Overview of the financial consequences for the alternatives (in million euro)*

| Project effects | Alternative | Reference (greenhouses) | Compensatiesteen | Formic acid |
|---|---|---|---|---|
| **Investment costs** | | **-€ 3,4** | **-€ 13,4** | **-€ 23,9** |
| **Operating costs** | | **-€ 0,6** | **-€ 5,4** | **-€ 18,5** |
| **Product revenue** | | **€ 0,7** | **€ 6,5** | **€ 7,8** |

The reference alternative has the lowest investment cost. This comes with a price and is mainly the reason why other alternatives were necessary to investigate. The low investment cost directly influences the production margin. The margin between the operating cost and product revenue is estimated at €0,1 million. This can be sufficient to make the reference alternative profitable in the long term but increases risk. If $CO_2$ prices drop, product revenue will instantaneously decline and create a situation in which the facility is no longer profitable.

The Compensatiesteen has significantly larger financial consequences. The investment cost (including the cost for carbon capture installation) is estimated at €13,4 million. For Meerlanden, this €10 million increase in investment cost is significant but not a deal-breaker. Along with these higher investment costs, the operating costs are significantly higher but product revenue also increases significantly. The difference between operating costs and product revenue leaves a product margin estimated at €0,9 million. This margin decreases risk compared to the reference alternative because it gives room to increasing operating costs or decreasing product revenue. Changes in these costs and benefits do not immediately impact the profitability of the project alternative.

The formic acid alternative has the highest investment cost and therefore also the largest immediate financial consequences. Besides the investment cost, the yearly operating costs are significant. As the process of producing direct electrochemical formic acid requires large amounts of electricity and specialized equipment and catalysts, the operating costs are high compared to the other alternatives. The drawback is that the reference price of the formic acid is not sufficient to generate a sufficient product margin. Reaching profitability without monetizing the indirect/external effects is therefore impossible.

## 6.2 Long term financial consequences

For the long term financial consequences, a financial cost-benefit analysis is used. The financial cost-benefit analysis uses the same input as the social cost-benefit analysis but ignores the external effects. Again, the net present value indicates the total net benefit of the proposed project alternatives. Project effects are discounted for 20 years of project duration and aggregated over the whole appraisal period. A positive NPV generally recommends implementing the proposed project.

The discount rate is formed by two parts, the risk-free interest rate, and the risk percentage. The economic stimulus from the ECB has led to an unprecedented drop in interest rates across the Eurozone. This impacts the risk-free interest rate on which the discount rate is based. The RWS assumes the risk-free interest rate at 0% (RWS Economie, 2020). The financial analysis uses a higher risk percentage compared to the SCBA. A risk percentage of 5% is assumed because external effects are not accounted for. All the benefits need to be generated by the production process and positive environmental effects will not contribute to the benefits. This increases risk, which needs to be accounted for. An 0% risk-free interest rate and a risk percentage of 5%, gives an effective discount rate of 5%. This rate is assumed to calculate the total net benefit of project alternatives. Table 27 shows an overview of the NPV of both project alternatives.

*Table 27: Overview of NPV with a higher discount rate of the two project alternatives (in million euro)*

| Project effects \| Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Investment costs** | **-10,0** | **-20,5** |
| **Operating costs** | **-64,9** | **-223,6** |
| Raw material cost | -29,6 | |
| Binding agent cost | -16,4 | |
| Electricity cost | -1,2 | -47,0 |
| Personnel cost | -6,8 | |
| Other costs | -10,9 | -176,6 |
| **Product revenue** | **78,3** | **94,3** |
| **FCBA total** | **3,4** | **-149,9** |

The NPV of the Compensatiesteen goes down compared to the base scenario with a lower discount rate. The FCBA value remains positive at €3,4 million. In the production period of 20 years, due to the difference between cost and benefits, the total net present value is a negative €149,9 million.

Based on the FCBA, the Compensatiesteen project alternative should be implemented based on the NPV. A positive NPV shows that, with current estimations and assumptions, such a facility will be profitable during the operation time of 20 years. The formic acid project alternative should not be implemented based on the negative NPV value. It will not be profitable for Meerlanden to invest in this project alternative.

## 6.3 Sensitivity analysis

Sensitivity analysis is used to show the robustness of the FCBA. Appendix E contains all the result tables from the different scenarios that are used to test for robustness. The results from the scenarios will be further explained in the following sections.

### 6.3.1 Investment cost

As the FCBA is financial analysis, a decrease in investment cost is expected to have a positive impact on the NPV. Both the low and high bound of the investment cost range is tested for the project alternatives. The NPV of the Compensatiesteen alternative becomes significantly more positive. The NPV of the formic acid alternative remains negative at a large negative value.

- FCBA Compensatiesteen €3,4 million to €5,4 million
- FCBA Formic acid €-149,9 million to €-145,4 million

Increasing the investment cost will have a negative impact on the NPV of both project alternatives. The NPV of the Compensatiesteen remains positive and could therefore still be advised to be implemented. The NPV of the formic acid alternative lowers even more and remains negative.

- FCBA Compensatiesteen €3,4 million to €1,4 million
- FCBA Formic acid €-149,9 million to €-154,4 million

### 6.3.2 Raw material cost

Raw material cost makes up a significant part of the operating costs of the Compensatiesteen project alternative. Changes in these costs can therefore have a large impact on the overall NPV. The formic acid alternative has no raw material costs like the Compensatiesteen alternative and therefore keeps the same NPV. Decreasing the raw material cost by 50%, significantly improves the NPV of the Compensatiesteen alternative.

- FCBA Compensatiesteen €3,4 million to €18,2 million
- FCBA Formic acid €-149,9 million to €-149,9 million

Increasing the raw material cost, as they make up a large part of the operating costs, will therefore have a negative effect. It shows that an increase of 50% in cost, will make the NPV significantly negative. This means that the project alternative could be relatively sensitive to changes in raw material cost and should be taken into account when looking further into this project alternative.

- FCBA Compensatiesteen €3,4 million to €-11,4 million
- FCBA Formic acid €-149,9 million to €-149,9 million

### 6.3.3 Binding agent cost

The binding agent cost is probably the main uncertainty of the Compensatiesteen project alternative. It is not clear which substance is used and the costs that are involved when using this product. An assumption is made for the base NPV but sensitivity analysis will highlight the impact that it could have on the project alternative. The formic acid project alternative does not use a binding agent and will therefore remain the same. A relatively small decrease of 50% in binding agent cost is tested. This leads to a significantly more positive NPV.

- FCBA Compensatiesteen €3,4 million to €11,6 million
- FCBA Formic acid €-149,9 million to €-149,9 million

A relatively small increase of 50%, already leads to a negative NPV. As the project alternative is heavily dependant on this binding agent, it makes up a large portion of the operating cost. A small change could have severe consequences for the feasibility of the project alternative.

- FCBA Compensatiesteen €3,4 million to €-4,8 million
- FCBA Formic acid €-149,9 million to €-149,9 million

The assumption was made that the binding agent could be 10 times more expensive than the quicklime, the second most expensive raw material involved in the production process. To test a far larger change, both a decrease and increase of 10 times will be analyzed for the effect on the project alternative. A decrease of 10 times the cost of the binding agent makes the NPV more positive.

- FCBA Compensatiesteen €3,4 million to €18,2 million
- FCBA Formic acid €-149,9 million to €-149,9 million

Increasing the price of the binding agent is expected to have a significant impact. It shows that it makes the project alternative overwhelmingly negative. Both analyses show that the project alternative is sensitive to the impact of the binding agent cost. As it makes up a large part of the operating cost and with the uncertainty about the price, further cooperation with the Ruwbouw group will be required to limit the uncertainty and sensitivity involved.

- FCBA Compensatiesteen €3,4 million to €-144,5 million
- FCBA Formic acid €-149,9 million to €-149,9 million

### 6.3.4 Electricity cost

Changing electricity cost is of large influence on the formic acid project alternative. As the process of electrolysis is used, large quantities of electricity will be necessary for the desired production capacity. Changes in the electricity price will directly influence the operating costs of both alternatives and thereby influence the NPV. A 50% lower electricity price will have a limited positive effect on the Compensatiesteen but the NPV stays positive. The decrease in electricity price will have a large impact on the NPV of the formic acid project alternative but can not ensure a positive NPV.

- FCBA Compensatiesteen €3,4 million to €4,0 million
- FCBA Formic acid €-149,9 million to €-126,3 million

An increase of 50% in electricity cost has similar opposing effects to the decrease in cost. The NPV of the Compensatiesteen alternative is expected to be lower but remains positive. Even with a higher electricity price, it could be feasible to implement. A higher electricity cost will make the formic acid alternative NPV even more negative. As even with free electricity, the NPV will not be positive. The increase in electricity costs will only make the situation less appealing.

- FCBA Compensatiesteen €3,4 million to €2,8 million
- FCBA Formic acid €-149,9 million to €-173,4 million

### 6.3.5 Overview of sensitivity analysis

The previous sections highlight the effect on the NPV of the different variations in the analysis. As an addition to these separate analyses and to give a clear overview of the different impact the variations have, tornado figures can be used. Figure 14 shows the sensitivity analysis for the FCBA of the Compensatiesteen project alternative. The project alternative is expected to be most sensitive to changes in the cost involved with the binding agent. The uncertainty about the specifications and the cost makes it highly uncertain. Expectations for the other effects were as assumed. The project alternative will also be relatively sensitive to changes in the raw material cost. These costs make up a large part of the operation costs, besides the binding agent, and changes in these costs have their impact on the NPV. Still, most analyzed changes lead to a positive NPV.

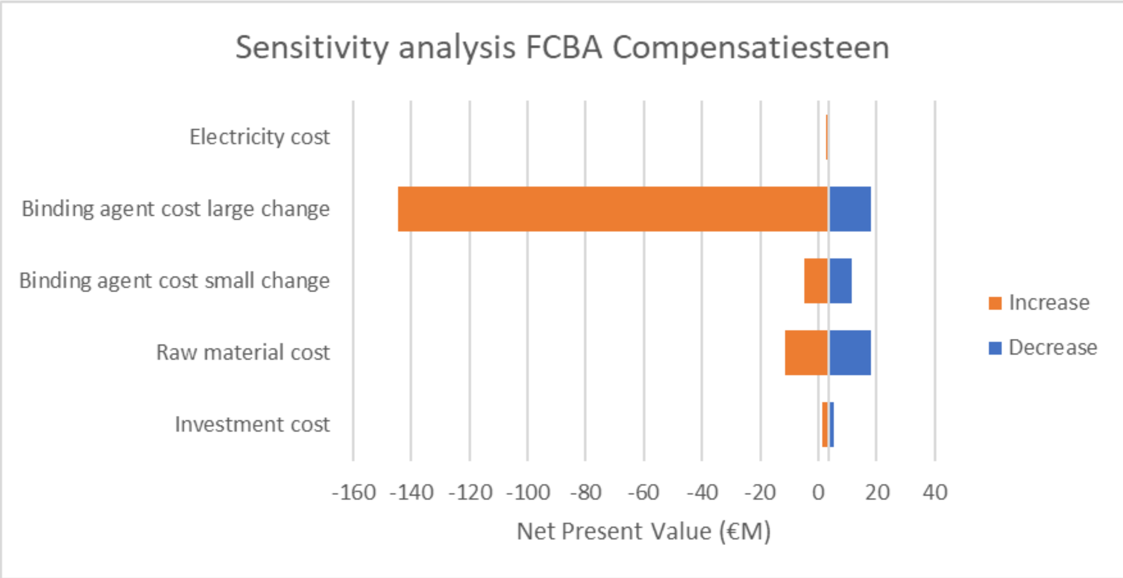


*Figure 14: Sensitivity analysis FCBA Compensatiesteen*

Figure 15 shows the results for the sensitivity analysis for the formic acid alternative. Only two included factors affect the financial cost-benefit analysis of this project alternative. Due to the large operating cost over a period of 20 years, the project alternative is sensitive to changes in electricity prices. As mentioned before, the process of electrolysis makes electricity a large part of the cost involved in the production process. The project alternative is less sensitive to changes in the investment cost because, compared to the operation costs, these are only a small part of the NPV.

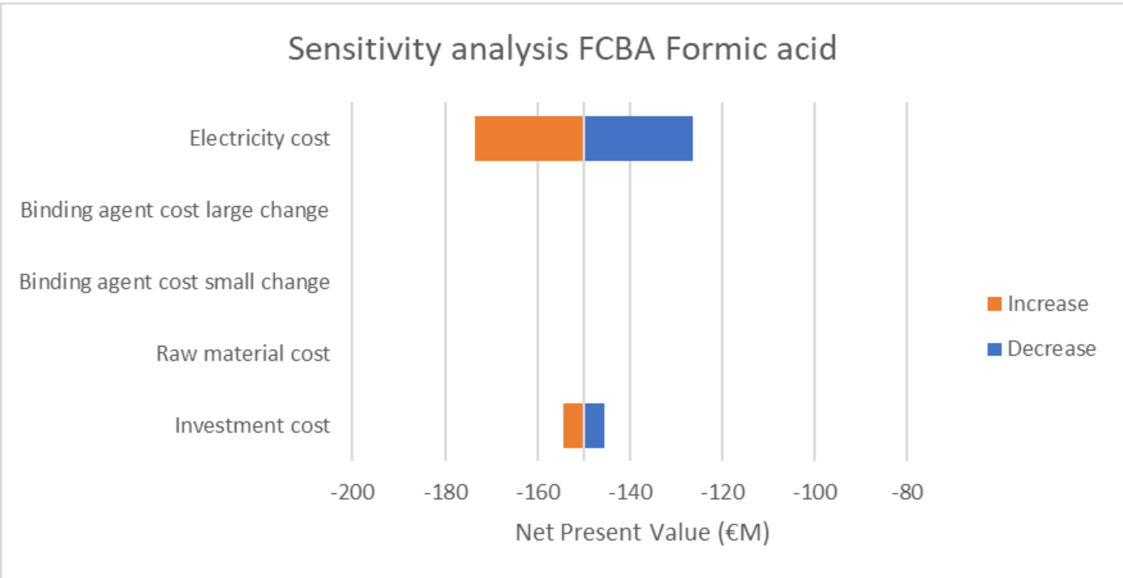


*Figure 15: Sensitivity analysis FCBA formic acid*

## 6.4 Conclusions

Based on the FCBA, the Compensatiesteen project alternative could be implemented as the NPV is positive. There are a lot of uncertainties involved and the sensitivity analysis has highlighted these. Especially the binding agent will be an important factor for the feasibility of such a facility at Meerlanden. Cooperation with the Ruwbouw groep will be required to supply the information needed to make an FCBA with less uncertainty.

The formic acid project alternative should not be implemented based on the NPV. Even though such a facility also includes uncertainties, it will be unlikely that a positive NPV can be reached. A decrease in electricity cost will not be sufficient to ensure a positive NPV and for this, the project alternative is most sensitive. Lower investment costs can also help in increase the potential but lower investment cost are highly unlikely and will still not be sufficient for a positive NPV.

# 7. Social cost-benefit analysis

Based on the information in chapter 5, an overview can be created for the project alternatives and the corresponding project effects. The valuations have not yet been corrected for the influence of time. The net present value is therefore an important part of the SCBA. The projects are operating for 20 years, so the project effects need to be corrected for the duration. Section 7.1 will present an overview of the NPV of the two project alternatives. Section 7.2 explains the results from the variant analysis and section 7.3 will explain the sensitivity analysis. The chapter will end with section 7.4 with the main conclusions about the social cost-benefit analysis.

## 7.1 Net present value

The net present value indicates the total net benefit of the project. Project effects are discounted for 20 years of project duration and aggregated over the whole appraisal period. A positive NPV generally recommends implementing the proposed project. In SCBA, a positive NPV also means that the project has a positive contribution to social welfare. In FCBA, a positive NPV signifies that the investment gives a financial return and should therefore be implemented.

The discount rate exists for the risk-free interest rate and the risk percentage. Stimulus ECB has led to an unprecedented drop in interest rates across the Eurozone. This impacts the risk-free interest rate on which the discount rate is based. The RWS assumes the risk-free interest rate at 0% (RWS Economie, 2020). The risk percentage is different between applications with the standard being 3%. The effective discount rate for the investments is therefore assumed to have similar rates as set by the RWS (2020). An 0% risk-free interest rate and a risk percentage of 3%, gives an effective discount rate of 3%. This rate is assumed to calculate the total net benefit of project alternatives.

## 7.2 Overview project alternatives

Using the NPV and the provided information of chapter 5, the valuations of the project alternatives are valued for the base year 2021. All the project effects are corrected for the influence of time and an overview is created to evaluate the results. Table 28 shows an overview of both alternatives.

*Table 28: Overview of base scenario NPV of the two project alternatives (in million euro)*

| Project effects | Alternative | Compensatiesteen | Formic acid |
|---|---|---|---|
| **Investment costs** | | **-10,0** | **-20,5** |
| **Operating costs** | | **-76,9** | **-265,0** |
| Raw material cost | | -35,1 | |
| Binding agent cost | | -19,5 | |
| Electricity cost | | -1,4 | -55,7 |
| Personnel cost | | -8,1 | |
| Other costs | | -12,9 | -209,3 |
| **Product revenue** | | **92,8** | **111,7** |
| **Environmental effects** | | **10,3** | **11,1** |
| Environmental benefits | | 10,6 | 11,2 |
| Environmental costs | | -0,3 | -0,1 |
| **SCBA total** | | **16,2** | **-162,7** |

The Compensatiesteen alternative has a positive social net present value of €16,2 million. Based on this result, it is recommended to implement the alternative, since it is expected to contribute to social welfare. The main driver of the positive net present value is high product revenue which is based on an average product price. When implementing a higher willingness to pay for products that, before the construction of houses, already contributes to the reduction of $CO_2$ emissions, and even higher product revenue can be expected. The environmental effects have a significant impact on the positive net present value.

The formic acid alternative has a very low social net present value. The main reason for this low social net present value is the difference between the operating cost and the reference price of formic acid. With 1500 €/ton formic acid in production cost and a reference price of 650€/ton, the difference is just too large to be compensated by the environmental effects. Implementing this alternative will therefore not contribute to social welfare. As the environmental effects should be used to compensate for the losses and should increase the net present value but the effects are too limited.

## 7.3 Variant analysis

When selling formic acid to the open market, the margins are just not high enough. As mentioned before, variant analysis can be used to change some characteristics of an alternative to evaluate the influence of this change. Using formic acid as a hydrogen carrier and thereby reducing the pollution generated by Meerlanden its heavy vehicles. The variant is tested for exchanging 14 green gas garbage trucks for formic acid vehicles. An overview of the effect on the alternative is shown in table 29.

*Table 29: Overview of base scenario NPV to compare formic acid truck variant (in million euro)*

| Project effects \| Alternative | Formic acid | Formic acid trucks |
|---|---|---|
| **Change in investment costs** | **-20,5** | **-€ 26,1** |
| **Change in operating costs** | **-265,0** | **-€ 265,1** |
| Change in raw material cost | | - |
| Change in binding agent cost | | - |
| Change in electricity cost | -55,7 | -€ 55,8 |
| Change in personnel cost | | - |
| Change in other costs | -209,3 | -€ 209,3 |
| **Change in product revenue** | **111,7** | **€ 111,7** |
| **Environmental effects** | **11,1** | **€ 11,8** |
| Environmental benefits | 11,2 | € 11,8 |
| Environmental costs | -0,1 | -€ 0,02 |
| **SCBA total** | **-162,7** | **-€ 167,7** |

The investment cost will increase due to the acquiring of these additional vehicles. As hydrogen vehicles in itself are relatively expensive, the formic acid installation will add even more costs to these vehicles. The main benefit of acquiring these vehicles is the reduction in air pollution and noise pollution. The variant analysis shows that there is a positive environmental effect and that these vehicles will help in reducing the pollution in urban areas. The downside is that the costs of these vehicles do not outweigh the benefits they cause.

## 7.4 Sensitivity analysis

Sensitivity analysis is used to show the robustness of the CBA. Appendix F contains all the result tables from the different scenarios that are used to test for robustness. The results from the scenarios will be further explained in the following sections.

### 7.4.1 $CO_2$ pricing

The €30 per ton carbon price is expected to be temporary. In the long term, the $CO_2$ price will increase. A $CO_2$ price of €100 per ton is said to be the required price to succeed in accomplishing the Paris climate agreement. When this price is used in the analysis, it has a large effect on the environmental benefits of both alternatives. The SCBA for the Compensatiesteen is expected to be positive with the current $CO_2$ pricing. When this price increases to €100 per ton, the NPV of Compensatisteen alternative increases to €40,3 million. The NPV of the formic acid alternative is negative with current $CO_2$ pricing. With the increase in environmental benefits, the NPV increases significantly but remains negative at minus €136,7 million

- SCBA Compensatiesteen €16,2 million to €40,3 million
- SCBA formic acid €-162,7 million to €-136,7 million

The second scenario is an even higher value of $CO_2$, at €200 per ton. In the analysis, this leads to an even larger increase in environmental benefits.

- SCBA Compensatiesteen 16,2 million to 74,9 million

- SCBA formic acid -162,7 million to -99,5 million

Both alternatives are significantly influenced by the change in $CO_2$ pricing in a positive way. Even with a CO2 price of €200 per ton, the formic acid alternative will not have a positive NPV. €470 per ton will be required to give the formic acid alternative a positive net present value. Such a large increase is unlikely but shows that, in terms of environmental benefits, in the long term a positive NPV should be possible when the other criteria remain constant.

### 7.4.2 Investment cost

The investment costs have a direct impact on the NPV. An investment cost range is used to estimate the costs for the different alternatives. The average is used for the main SCBA. For the sensitivity analysis, the lower and higher bound of the investment cost ranges is tested. A low investment cost leads to a small increase in NPV for both alternatives. As both projects have large total operating costs and benefits for 20 years, a small decrease in investment cost has a limited impact on the NPV.

- SCBA Compensatiesteen 16,2 million to 18,2 million
- SCBA formic acid -162,7 million to -158,2 million

High investment costs negatively impact the NPV. Again, in comparison to the total value of the operating costs and benefits of the production, the impact is limited. The NPV of both alternatives decreases but the Compensatiesteen alternative remains positive.

- SCBA Compensatiesteen 16,2 million to 14,2 million
- SCBA formic acid -162,7 million to -167,2 million

The total impact of the investment cost is limited on both alternatives. Investment costs can make a difference in the realization of alternatives because of stakeholder preference for lower investment costs. For the NPV of both alternatives, the impact is limited.

### 7.4.3 Raw material pricing

Raw material pricing can make a large difference in the NPV of the Compensatiesteen alternative. The main SCBA is based on market prices from the required raw materials (Sand, quicklime). A lower raw material price of 50% is used to test the impact on the NPV. This increases the NPV significantly. As the formic acid alternative does not use these raw materials, the NPV does not change.

- SCBA Compensatiesteen 16,2 million to 33,7 million
- SCBA formic acid no change

High raw material prices significantly increase operating costs. An increase of 50% is assumed to test the sensitivity for raw material prices. This results in a negative NPV for the Compensatiesteen alternative. With such high raw material prices, the project alternative would become undesirable.

- SCBA Compensatiesteen 16,2 million to -1,4 million
- SCBA formic acid no change

As raw material costs make up a significant part of the operating costs, a high price will make the social net present value negative. In that case, the project should not be implemented. As expected, lower raw material costs generate an even better business case for the Compensatiesteen alternative with a significantly higher NPV.

### 7.4.4 Binding agent cost

The binding agent plays an important role in the implementation of the Compensatesteen alternative. It is unclear what type of binding agent is used, and therefore assumptions are made about the price of the binding agent. A decrease in the binding agent cost of 50%, increases the NPV of the alternative to €25,9 million. The formic acid alternative does not change.

- SCBA Compensatiesteen 16,2 million to 25,9 million
- SCBA formic acid no change

High binding agent cost decreases the NPV of the Compensatiesteen alternative to 6,5 million. Even though this is a significant decrease, the NPV remains positive and could therefore be implemented.

- SCBA Compensatiesteen 16,2 million to 6,5 million
- SCBA formic acid  no change

The previously made changes are relatively small compared to the base assumption price for the binding agent. A far larger change will also be tested to see its impact on the overall social cost-benefit of the project alternative. A price 10 times smaller (€200 per ton) is used to see its impact. This leads to an even larger positive social net benefit. The formic acid alternative does not change again, as no binding agent is used.

- SCBA Compensatiesteen 16,2 million to 33,7 million
- SCBA formic acid no change

A far larger price, a factor 10, increase in the binding agent will also have a significant impact. As the exact nature of the product, and thereby the price is unknown, include such a large change will tell something about the uncertainty involved in the project alternative. With a binding agent cost of €20000 per ton, the social cost-benefit of the project alternative comes down to a negative value of -159,1 million.

- SCBA Compensatiesteen 16,2 million to -159,1 million
- SCBA formic acid  no change

### 7.4.5 Electricity costs

Electricity costs make up a significant part of the operating costs of the project alternatives, especially the formic acid alternative. The use of electrolysis for the production of hydrogen requires large amounts of electricity. The electricity costs for the Compensatiesteen project alternative are limited because of a $CO_2$ based production process that does not require large amounts of electricity. A decrease of 50% in electricity costs has a limited impact on the Compensatiesteen project alternative. The NPV of the formic acid project alternative remains negative but improves with almost 30 million.

- SCBA Compensatiesteen 16,2 million to 16,9 million
- SCBA formic acid -162,7 million to -134,8 million

High electricity costs will lead to higher operating costs. Again, the impact of the Compensatiesteen project alternative is limited but significantly impacts the formic acid project alternative. This time it decreases the NPV by almost 30 million.

- SCBA Compensatiesteen 16,2 million to 14,8 million
- SCBA formic acid -162,7 million to -190,6 million

A lower electricity price has a significant impact on the overall social net present value of the formic acid project alternative. Because of electrolysis for hydrogen, electricity takes up a large part of the operating costs. Besides the electricity costs, other costs (rare metals as catalysts, etc) still make up the largest part of the operation cost. A halving of the electricity price can therefore not make a positive social net present value for the formic acid alternative. Even free electricity will not guarantee, with the information from Pérez-Fortes & Tzimas, a positive net present value.

### 7.4.6 Overview of sensitivity analysis

The previous sections highlight the effect on the NPV of the different variations in the analysis. As an addition to these separate analyses and to give a clear overview of the different impact the variations have, tornado figures can be used. Figure 16 shows the sensitivity analysis for the SCBA of the Compensatiesteen project alternative. It becomes clear that a large change in the binding agent cost can have an enormous impact on the NPV of the project alternative. As mentioned before, the binding agent is probably the largest uncertainty involved with this project alternative. If the costs for the binding agent are far larger than assumed, the NPV becomes very negative and the project alternative should not be implemented. Besides the binding agent costs, the increase in $CO_2$ price has a relatively large impact. Electricity cost, raw material cost, and investment cost all have a relatively small impact on the overall NPV of the project alternative. Cost changes for these effects are also less uncertain than binding agent costs and the valuation of $CO_2$.

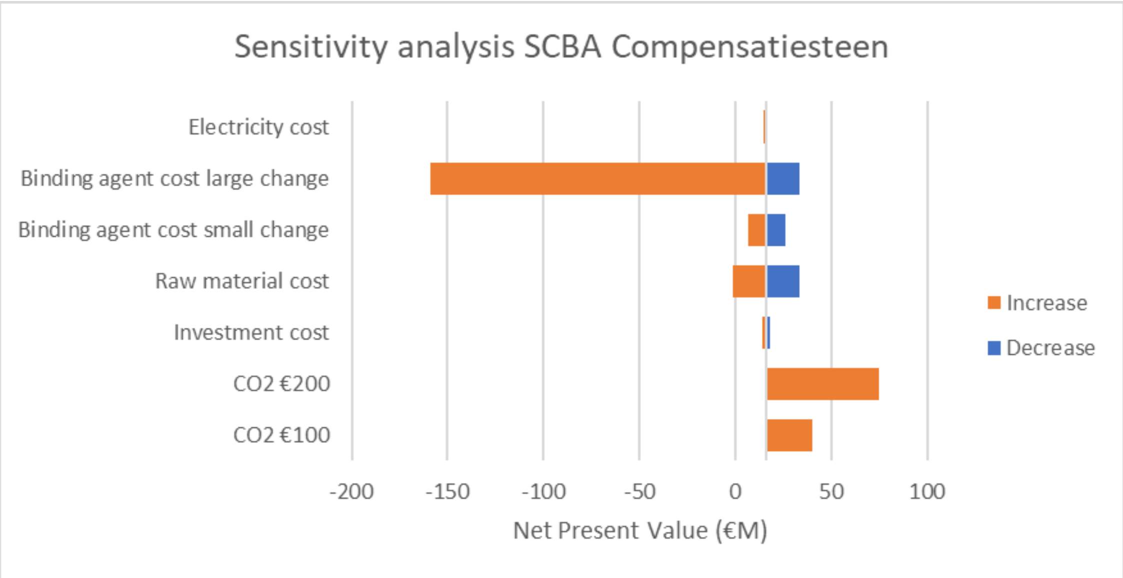


*Figure 16: Sensitivity analysis SCBA Compensatiesteen*

Figure 17 shows the sensitivity analysis for the Formic acid project alternative. The base NPV for this project alternative has a negative value. No change in effects is large enough to generate a positive value for the NPV. The large increase in $CO_2$ price to €200 per ton can help the most in reducing the negative NPV. Besides the $CO_2$ price, an electricity cost reduction can also help to reduce the negative NPV of this project alternative.

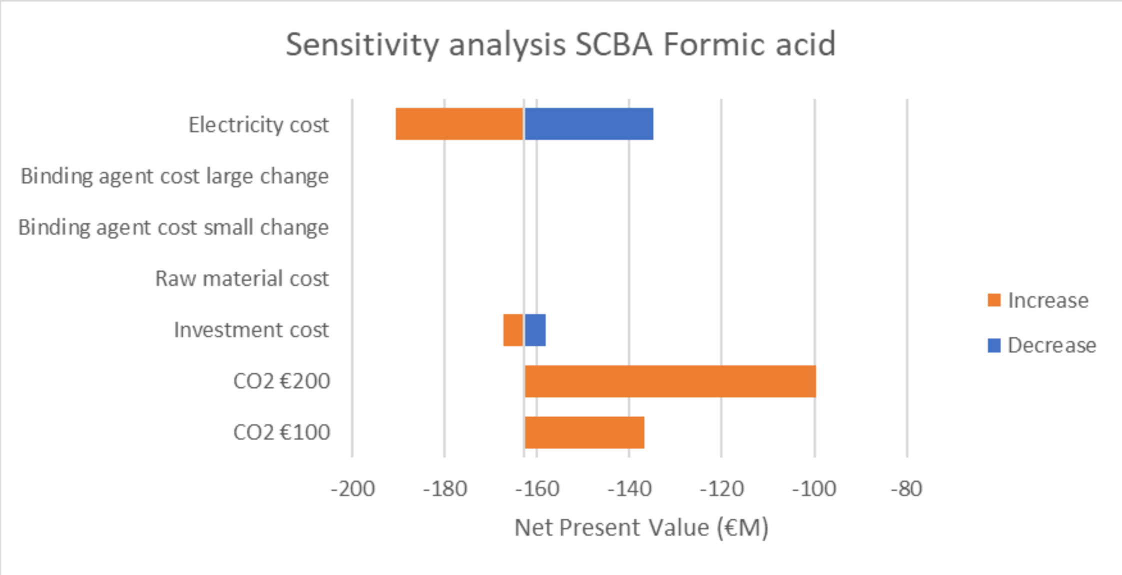


*Figure 17: Sensitivity analysis SCBA Formic acid*

## 7.5 Conclusions

This chapter has presented the results of the social cost-benefit analysis of both project alternatives, Compensatiesteen, and formic acid. The compensatiesteen alternative has a positive SCBA under the standard scenario. With the made assumptions and estimations, the project should contribute to social welfare and therefore be implemented. The formic acid alternative does not have a positive SCBA. The project should therefore not be implemented.

This chapter also discussed the results of different tests to examine the robustness/sensitivity of the CBA results. A variant in which the formic acid will be used by Meerlanden with the purchase of 14 heavy vehicles for garbage collection will not ensure a positive net present value. The positive environmental effects can not compensate for the large difference between the reference price of formic acid and the operating costs.

A higher $CO_2$ price will make both alternatives more attractive but won't ensure a positive net present value for the formic acid alternative. A $CO_2$ price of 470€/ton will be required to give a positive net present value to the formic acid alternative. High raw material costs will give the Compensatiesteen alternative a negative net present value. Ensuring the exact ratio and prices of raw materials will be important before investments are made. The used binding agent has a significant role in the advice to implement the Compensatiesteen alternative. This means that a further increase in price for the binding agent will lead to a negative net present value and thereby a negative implementation advise. Electricity costs are of significant influence on the formic acid alternative but even free electricity can not guarantee a positive net present value. The other costs involved in the process are currently simply too high to ensure positive outcomes.

# 8. Conclusions and recommendations

In this chapter, the conclusions of the research and recommendations will be presented. The results that can answer the main and sub research questions will be included in section 7.1. Based on these conclusions, recommendations will be given to Meerlanden in section 7.2.

The main research question that will be answered is: *To what extent will the implementation of carbon capture and utilization at small biomass plants be beneficial from the business perspective and the perspective of society?*

## 8.1 Conclusions

The objective of the research was to identify the cost and benefits associated with carbon capture and utilization at small biomass plants. These results are used to make recommendations for Meerlanden and the possibilities for carbon capture and utilization at their biomass plants. Besides the direct recommendations for Meerlanden, the research will give more insight into the opportunities for small scale carbon capture and utilization. As the research is partly based on estimations, assumptions, and involve uncertainties, the results should be used as a basis for further in-depth research. Additional information, that is currently not public, should be used to get results with more certainty.

The first sub-question as a start for the research was as follows: *What are the potential alternatives of carbon utilization for Meerlanden?*

As carbon capture and utilization is a broad term, specific technologies have advantages and disadvantages depending on the characteristics of the stakeholder. The research did not go further into the carbon capture aspect of the proposed facilities. Frames B.V. provided a suitable technology based on the characteristics of the biomass plant as set by Meerlanden. Along with this technology, they provided information about the investment and operating costs of such a carbon capture installation.

A selection of potential carbon utilization technologies was created based on a literature review. All these carbon utilization alternatives could be viable for small or large scale biomass plants, especially in combination with the carbon capture technology from Frames B.V. With the use of the AHP for the criteria, this selection of carbon utilization has been weighted in an MCA. The best scoring project alternatives were the Compensatiesteen and formic acid project alternatives.

The Compensatiesteen alternative is the only project alternative with long-term carbon storage potential. As the production process stores 250 kg $CO_2$ per ton of Compensatiesteen, all the captured $CO_2$ from the biomass plant can be stored. In comparison, the other project alternatives will save carbon emissions but the captured $CO_2$ will return to the atmosphere relatively shortly after capture. Besides the carbon storage potential, it also scored high due to the added value of the production process. This process adds a lot of value to the captured $CO_2$ compared to the delivery of the $CO_2$ to greenhouses.

The formic acid project alternative has the most added value per ton of $CO_2$. The main reason for this is due to the production process and the fact that it can be used as a hydrogen carrier. This is especially interesting for Meerlanden as they are searching for methods to make their waste collection more sustainable. Their current generation of garbage trucks uses CNG, generated from their green energy factory. Even though the source is renewable, this method still causes the emission of exhaust gasses in urban areas. To replace these vehicles, formic acid-based vehicles could limit inner-city pollution and make their process more renewable.

The second sub-question was**:** *What are the financial consequences for Meerlanden?*

The two project alternatives with the highest potential from the MCA were further analyzed to estimate the financial costs and benefits. The financial consequences follow from an FCBA based on the general cost-benefit analysis effects. Depending on which alternative is chosen, the investment costs vary greatly. In comparison to the reference alternative, the Compensatiesteen alternative is with €13,4 million the least expensive project alternative. The formic acid alternative requires an investment of around €23,9 million.

Besides the investment costs, the operating costs will be of considerable size. The Compensatiesteen alternative is estimated to have around €5,4 million of yearly operating costs. These mainly consist of raw material, personnel, maintenance, and other costs. The operating costs of the formic acid alternative are more than 3 times as high, at €18,5 million per year. The direct electrochemical conversion of $CO_2$ to formic acid requires large amounts of electricity, which leads to significant operating costs. In addition to the electricity cost, expensive catalysts are required to facilitate the process.

Positive financial consequences come in the form of product revenue. Gaseous $CO_2$ to greenhouses leads to significantly lower product revenue compared to the two project alternatives. The estimation is that, based on the made assumptions, the product revenue for the Compensatiesteen alternative will be around €6,5 million per year. Changes in product price can be of large influence on the whole business case as it directly impacts the benefits. This also counts for the formic acid alternative with a product revenue of €7,8 million per year. A higher product revenue can significantly improve the business case but a large price increase is required to make the alternative profitable.

With the use of a discount rate of 5%, higher to compensate for the business risk involved, the NPV for the two project alternatives are positive and negative. The Compensatiesteen alternative could be implemented due to a net present value of €3,4 million. The formic acid alternative has a very large negative NPV with €149,9 million. This project alternative should therefore not be implemented.

Both project alternatives involve a certain amount of uncertainty. The largest uncertainty is the binding agent cost for the Compensatiesteen project alternative. The Ruwbouw groep has not made public which substance is used and therefore, an exact price is impossible to determine. Sensitivity analysis provides insight into the effects and highlights that the project alternative is sensitive to large price changes. Electricity price is not that uncertain but the formic acid project alternative is sensitive to it. As electrolysis is used for production, large quantities of electricity will be required. The price of electricity therefore determines a large part of the operation cost involved in the production process of formic acid.

The third sub-question was**:** *What are the social costs and benefits of the different carbon capture and utilization options?*

An SCBA is conducted to evaluate the social costs and benefits of the proposed carbon utilization options. With these costs and benefits, the contribution to the social welfare of the project alternatives can be determined. It involves all direct/indirect and external effects associated with the project alternatives. Investment costs, operating costs, and product revenue are necessary to determine the outcome of the project alternatives. The difference compared to the FCBA are the environmental effects. The climate change costs (mainly $CO_2$), air pollution and, noise pollution caused by the implementation of the project alternatives have been included. These are the cost to society that can significantly impact social welfare.

The compensatiesteen project alternative has a positive net present value of €16,2 million over 20 years. This means that the project alternatives should be implemented and that the impact on social welfare will be positive. Environmental costs are limited with the Compensatiesteen and estimated at €0,3 million. These costs are associated with the transport of raw materials to the facility in Rijsenhout. This causes air pollution, noise pollution and has climate change costs in terms of $CO_2$ emission by the heavy transport vehicles. The social benefits outway the costs and are estimate at €10,6 million. The main reason for these large benefits is the $CO_2$ emission reduction compared to the traditional production of sand-limestone bricks.

The formic acid project alternative can not reach a positive net present value due to the large difference between operating costs and product revenue. The NPV is negative at €162,7 million. This means that the project alternative should not be implemented as it will not contribute to social welfare. The social costs are limited to €0,1 million. Limited transport is the main reason for this small negative environmental impact. The environmental benefits, also the social benefits, are larger with €11,2 million. This is due to the large reduction in $CO_2$ emissions compared to traditional formic acid production based on fossil fuels.

Sensitivity plays a large role in the results for both project alternatives. It shows that the Compensatiesteen alternative is highly sensitive to changes in the binding agent cost. Besides this, $CO_2$ pricing can have a large impact on the social cost-benefit of the Compensatiesteen alternative. For reference, the current $CO_2$ price of €30 per ton is taken. If this price increases, it will significantly impact the Compensatiesteen positive contribution to social welfare. This is also the case for the formic acid project alternative. Even though the price increase of $CO_2$ needs to be large, it could help in making such facilities feasible in the future.

With the results from the three sub-questions, the main research question can be answered: *To what extent will the implementation of carbon capture and utilization at small biomass plants be beneficial from the business perspective and the perspective of society?*

The results show that there are different possibilities for carbon capture and utilization, even for small biomass plants. This is a positive result that can be taken into account when looking further into the implementation of small biomass plants. It is important to note that uncertainty has a significant impact on the outcome of this research. The analysis shows that there are possibilities for a positive NPV with the Compensatiesteen but only when there are no large changes compared to the assumptions made to analyze the project alternative.

From the business perspective, it becomes clear that formic acid production with direct electrochemical conversion is not a suitable option. The difference between the operating costs and product revenue is too large to ever make a profit in current conditions. If the electricity price goes down, the technology develops, and the price of formic acid increases, then it can become a suitable option from the business perspective. Even an electricity price drop and a product price increase can not compensate for the larger difference. The results for the Compensatiesteen alternative are positive from the business perspective and could therefore be suitable for implementation. The high level of uncertainty makes additional research, with concrete information, necessary to validate this conclusion.

From the perspective of society, only the Compensatiesteen alternative can contribute to an increase in social welfare. The formic acid alternative has a similar social impact but this is not sufficient to compensate for the difference in operating costs and product revenue. Therefore, it does not contribute to the increase in social welfare.

Based on these two examples and the estimations that are made, it shows that carbon capture and utilization could be beneficial from the business perspective and the perspective of society. The type of technology greatly determines if implementation will be beneficial. It is in line with the expectations that technology, like the Compensatiesteen, can be beneficial in terms of business perspective. The Ruwbouw groep, which developed this specific type of method, is in the process of expanding its production facilities. Even though the analysis is influenced by uncertainty, as they are expanding their production facilities there are possibilities for a profitable business. The formic acid production process shows that for now, the implementation of hydrogen driven production is unlikely to be beneficial. Production processes, technology, prices, and other factors lead to high costs that, at least for now, can not compete with fossil-based products.

## 8.2 Recommendations

The goal of this research was to advise Meerlanden on possibilities for carbon capture and utilization. Based on the results, such advice can be formulated.

It becomes clear that, under the right circumstances, a facility that produces Compensatiesteen can be beneficial for Meerlanden. The experience with heavy machinery, the availability of heavy machinery, the location, and the available $CO_2$ all contribute to the attractiveness of such a facility. The downside is that the recommendation is based on assumptions, especially about the ratio of raw materials and the exact nature of the required raw materials. It is therefore recommended to further investigate the exact production process of the Compensatiesteen or a similar product. If it becomes clear that due to licensing or patents, the production of such Compensatiesteen tends to be impossible, other alternatives can be sought that are based on the same principle. The Ruwbouw groep has found a way to directly produce building material from $CO_2$ and raw materials but some alternatives make it possible to produce the intermediate products with $CO_2$. If Meerlanden is interested, based on the analysis, in such a production facility, further communication with the Ruwbouw groep is recommended. Additional research about their production process will not be required as their data is not publicly available. To move forward, conversations need to take place.

Besides the fact that a project alternative, Compensatiesteen, could positively contribute to social welfare, it is recommended to take note of the carbon capture technology itself. Because of this research and therefore, communication with Frames B.V., has provided further insight into the costs of carbon capture technology. The reference alternative is therefore a sufficient proposal that can help to increase social welfare. Based on their provided data and assumptions about other costs involved, it showed that the NPV of carbon capture and utilization by providing greenhouses with $CO_2$ also has a positive NPV. If the recommended project alternative can not be implemented or is found undesirable by stakeholders, the reference alternative could still have a positive contribution to social welfare.

Even though only the Compensatiesteen project alternative shows a positive NPV, such facilities can help in changing the narrative about biomass plants. In recent months, the debate in the Netherlands has shifted 180 degrees. To such extent that the planned facility from Meerlanden is put on hold. The plans, the licenses, the subsidies, everything is ready for implementation but tenders are made impossible according to Meerlanden. National politics has increased the uncertainty to such an extent that companies do not dare to become involved in such tenders. Carbon capture and utilization can help in shifting the debate. At least change the fact that all biomass installations are treated equally when this is not the case. Meerlanden provides almost all the required biomass and does not demand biomass from other countries. The biomass plant could be used as a basis for a heat network on which datacenters in the area could connect. Promising plans about carbon capture and utilization can assist in changing this debate.

# 9. Discussion and reflection

In this chapter, the discussion and reflection of the research will be described. It will contribute to a better understanding of the research context and the relevance of the research. Last, an overview of future research is given.

## 9.1 Reflection on research

All research comes with limitations. The limitations of the conducted will be discussed and the possible impact on the results will be further described.

The main limitation of the research is data related. For both the MCA and SCBA, concrete and validated data will provide more solid and reliable results. As most technologies are not widely implemented, exact data about the carbon utilization technologies are scarce. Especially data about the exact costs (investment and operating) is most often unavailable. This leads to assumptions and estimations which have a direct impact on the results. By using, for example, cost ranges based on multiple sources limits the impact of these assumptions. Besides the unavailable data, the exact nature of the production process of the Compensatiesteen alternative has had a significant impact. This has lead to the fact that more assumptions were needed to calculate the operation costs in terms of raw material usage. By using sensitivity analysis, this risk is somewhat mitigated and the impact of changes in the assumed costs is identified. This all can not prevent the impact of unclear data for the FCBA and SCBA.

A range of possible carbon utilization options was identified for the MCA. Only two project alternatives were selected for conducting the SCBA. This gives the possibility to further analyze these best scoring alternatives but leaves the other project alternatives out. There is a possibility that, even with a relatively low score in the MCA, the overall NPV of some of the other project alternatives could have been positive. They could have a positive contribution to social welfare when implemented but by not further analyzing, these effects are not clear.

The research is based on the selection of the best scoring project alternatives and these two alternatives are further analyzed. The selection is based on the weights given by an AHP. The AHP is conducted in cooperation with Meerlanden and weights the criteria based on their preferences and situation. The research is therefore focused on companies with similar characteristics as Meerlanden. They have, for example, access to financing with low-interest rates due to their shareholders being municipalities. This makes the criteria ‘investment costs’ less important under the condition that the business case is solid. The complexity of the production process is for Meerlanden a relatively important criterion because they are not necessarily a high tech company. Highly complex processes would lead to a significant change in the company, which for now, is deemed undesirable. These preferences of Meerlanden ultimately create a bias for certain project alternatives.

## 9.2 Scientific relevance

The research is focused on advice for Meerlanden which leads to more practical and less theoretical analysis. The scientific relevance is found in the possibilities for carbon utilization at small biomass plants. Most of the time it is assumed that large installations are required to create a suitable business case for carbon capture and utilization. This research shows that, under specific circumstances, carbon capture and utilization is possible at small biomass plants. Even though the made assumptions introduce uncertainty to the research, it does limit the possibilities. It can lead to further research and case studies that can help in realizing carbon capture and utilization facilities.

Besides the possibilities, it shows how large the role of regionality can be to find suitable carbon utilization options. As small biomass plants are located all around the Netherlands, by using carbon capture and utilization, products can be created close to the demand. As for Meerlanden, in the area of Haarlemmermeer, around 30000 houses are planned to be constructed in the coming decade. By using, for example, a Compensatiesteen facility in the area, a significant amount of building materials do not have to be supplied from further away. This focus on regionality can be an important factor in terms of sustainability and adds scientific relevance to the research. Instead of focusing on the costs and benefits involved in certain project alternatives, the focus could be on the regionality as this also creates added value. Especially when involved with stakeholders that are actively taking part in working towards a circular economy.

For formic acid, this research shows that feasible facilities are unlikely to be realized soon. The difference between cost and benefits is just too large to simply overcome. Besides the differences in cost and benefits, the environmental impact is relatively limited. This leads to the requirement of a very high $CO_2$ price to be able to realize a positive NPV and thereby, a positive contribution to social welfare.

The method used for this research gives insight into the possibilities for carbon capture and utilization but inherently introduces uncertainty into the research. Only Frames, the manufacturer of carbon capture installations, was open about their process and costs. Due to the nature of this technology and the fact that everything is relatively new, most information is vague or not available at all. This limits the suitability of cost-benefit analysis for such problems as estimations will be required to conduct the research. If more concrete information was available, this would significantly increase the value of such research for carbon capture and utilization options.

## 9.3 Societal relevance

As companies and governments try to comply with their sustainability goals for 2030 and 2050, more and more technological innovations will be required. The research shows that there may be more possibilities for carbon utilization then people and companies assume. Besides a large amount of possible carbon capture and utilization options, it opens up the debate about small biomass plants. As mentioned before, the debate in the Netherlands has shifted against biomass-based energy generation. The possibilities of increasing social welfare by adding carbon capture and utilization to biomass plants can be an argument for biomass use.

Some assumptions and estimations are based on the characteristics of Meerlanden. As Meerlanden is a company with its own supply of biomass, knowledge about biobased processes, having municipalities as shareholders, and access to heavy machinery, not a lot of companies can be compared to them. Therefore, the results of this research can only be generalized to a certain level. As Meerlanden is located in the Haarlemmermeer and services that area, there will be other companies that handle the organic waste in other parts of the Netherlands. The results could be also applicable to them. Especially access to regional biomass became a large issue. With biomass, in general, falling out of favor, local/regional biomass could become a requirement for the implementation of biomass. For other companies that have access to such a resource, this research could be used to evaluate their possibilities and can be used as a starting point for investigating their business case for carbon capture and utilization.

## 9.4 Political implication of biomass

Biomass implementation, mainly electricity generation, is one of the pillars of the Dutch climate agreement. Biomass is classified as a renewable energy source, implementing biomass installations would therefore reduce Dutch greenhouses emission (mainly $CO_2$) and contribute to the 2030 and 2050 emission reduction goals. The subsidy involved and the lowering of emission standards, has led to a large increase in biomass installations. In June 2020, 153 new biomass installations were being constructed which brought the total to 372 biomass installations in the Netherlands (Pennings, 2020). This large increase has led to opposition in society and has divided policymakers.

25 June 2020, the Dutch coalition decided to end the subsidy for biomass plants that only generated electricity (van Dijk & Knoop, 2020). This has increased the opposition to biomass plants even more and no distinction is made between biomass plants. Biomass plants is the general term used for all types of installations. Large, small, producing electricity or generating heat, they all belong to the same category for society and policymakers. With the subsidy, a business case is made based on biomass use and the installation is constructed. Meerlanden has worked the other way around but is now negatively impacted by the opposition formed in society. This opposition has impacted the political climate which makes the implementation of their plans in Rijsenhout even more difficult.

Existing coal-fired plants used co-firing to make their facility more renewable. These large amounts of biomass are not available in the Netherlands and therefore have to be imported. This has a severe negative effect on the local ecosystem from which the biomass originates. Besides co-firing, due to the available subsidy, small biomass plants have been constructed as mentioned before. Most often, the required biomass also needs to be imported which has a similar negative impact. Meerlanden has worked the other way around compared to other installations. As Meerlanden is a waste management organization, they have access to a certain amount of woody biomass. Based on this average yearly supply, they planned a biomass plant to make use of this resource. Heat for neighboring Schiphol-Rijk was the main goal and the installation would be the base for a regional heat network. As the Haarlemmeer has access to heat from data centers, these could be connected to the heat network. Without a steady supplier of heat, like a biomass plant, the data centers would not be interested in joining the heat network as they can not ensure heat supply at all times.

Due to the political climate and the implications, it has on the construction of biomass plants, Meerlanden has been forced into a difficult position. The analysis of regional biomass combined with carbon capture and utilization can contribute to changing the political opinion.

## 9.5 Future research

The reflection and discussion in the previous sections provide recommendations for future research. The main recommendation for further research is to investigate the possibilities of Compensatiesteen facilities with exact characteristics and data. With a shortage of housing and a large number of biomass plants, this could open up possibilities for small production facilities around the Netherlands to produce high-quality sustainable building materials close to potential buyers.

Even though formic acid production does not seem like a viable option, it offers a range of possibilities. The use as a hydrogen carrier for transport and the electrochemical conversion of $CO_2$ into formic acid are both analyzed separately. Future research should be focused on combining these two aspects. Producing formic acid as a transport fuel with $CO_2$ captured from biomass plants could potentially be a sustainable solution for some companies that have difficulties in reducing their $CO_2$ emissions.

As the debate about biomass has shifted and society has a negative view of biomass, future research could investigate if these opinions shift when carbon capture and utilization are included. This can help to open up the debate and shift the balance towards biomass usage. Especially for Meerlanden, when biomass is collected regionally.

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## Appendix A: Carbon capture

In 2019, only five facilities in the world were actively using carbon capture and storage combined with bio-energy (Global CCS Institute, 2019). 18 more facilities are also using carbon capture with a biomass feedstock but most of these facilities are in ethanol production. The operating principles behind carbon capture are based on three main technologies. Post-combustion, pre-combustion and oxy-combustion are the most used methods of carbon capture. The systems of these three main technologies are shown in figure 18.

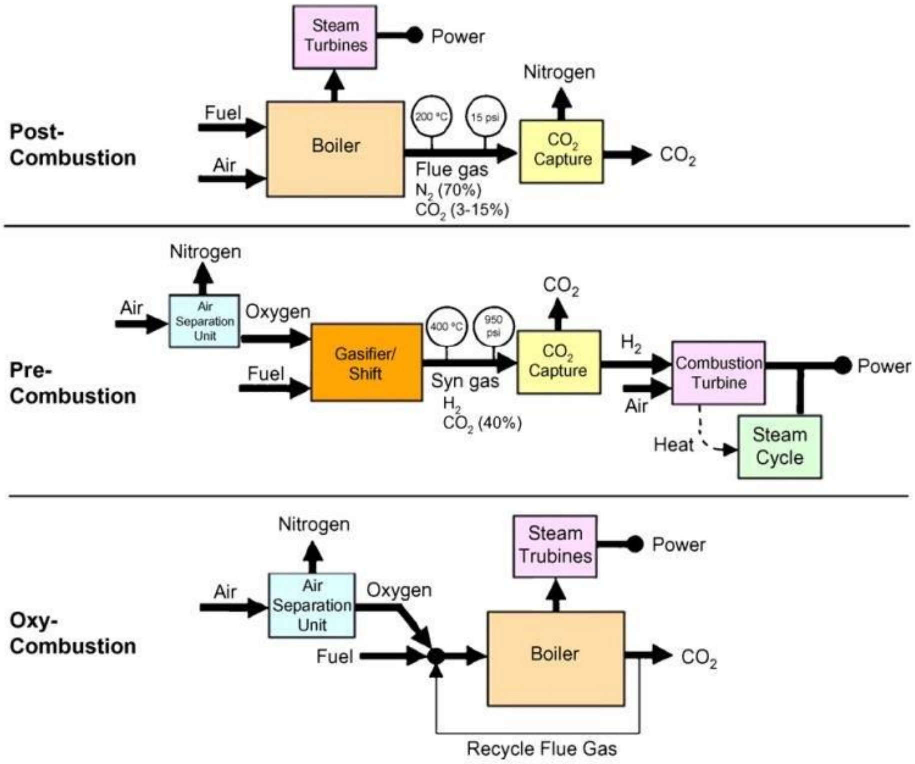


*Figure 18:Scheme of main carbon capture systems (Wu et al., 2018)*

Post-combustion is the technology that is most often used to retrofit existing facilities with carbon capture (Lucquiaud & Gibbins, 2011). It is an 'end of pipe solution' and will be suitable for more existing installations compared to pre-combustion and oxy-combustion. Post-combustion functions by directly 'filtering' the flue gasses and thereby removing the CO2 from the flue gasses. The actual removal of the CO2 from flue gas can be done by a range of technologies. Absorption, adsorption, cryogenic, and membrane technologies are all being investigated to be used for post-combustion CO2 capture (Songolzadeh *et al.,* 2014). To make carbon capture a viable option, the used technology is required to be efficient with low operating costs and energy consumption.

Pre-combustion carbon capture uses a more 'complicated' process and is less suited for existing energy plants (Erlach, Smidt & Tsatsaronis, 2011). Figure 2 also shows the process of pre-combustion carbon capture. The fuel is used, with oxygen, to create syngas. Syngas is a combination of H2 and CO2 with a 40% CO2 concentration. Because of this higher concentration, removing the CO2 from the fuel gas becomes easier compared to the removal of CO2 from flue gas. The H2 is then burned to create the required power or heat without emitting further CO2. Due to the extra steps in the process, investment costs in pre-combustion technology are significantly higher and less suitable for existing installations. Furthermore, this technology is most suitable for coal-fired energy plants because of the gasification process.

Oxy-combustion is a relatively new but promising technology to facilitate carbon capture (Jurado *et al.,* 2015). It changes the combustion process by using enriched oxygen with recycled flue gasses to increase the concentration of CO2 in the flue gas. The recycled flue gasses are used to control the temperature in the combustion chamber (Stanger *et al.,* 2015). This technology removes the necessity of energy inefficient solvent use (post-combustion) or complicated pre-combustion steps. By reaching a CO2 concentration of 70% after combustion because of the enriched oxygen use, minimal flue gas treatment is needed to increase the concentration even more. It could also be a viable technology to be used in combination with biomass (Sher *et al.,* 2018).

# Appendix B: Literature review tables

*Table 30: Literature review table carbon capture*

| | BECCS | BECCU | CCU | CCS |
|---|---|---|---|---|
| Aldaco et al. (2019) | | | x | |
| Azar, Lindgren, Larson & Möllersten. (2006) | x | | | |
| Azar et al. (2010) | x | | | |
| Budinis et al. (2018) | | | | x |
| Cheah et al. (2016) | | | x | x |
| Cuéllar-Franca & Azapagic. (2015) | | | x | x |
| Gough & Upham. (2011) | x | | | |
| Hepburn et al. (2018) | | | x | |
| Kuramoch, Faaij, Ramirez & Turkenburg. (2010) | | | | x |
| Larson, Jin & Celik. (2005) | x | | | |
| Moncada, Posada & Ramirez. (2015) | | x | | |
| Pérez-Fortes et al. (2016) | | | x | |
| Rahman et al. (2017) | | | x | x |
| Schmidt et al. (2010) | x | | | |
| Størset et al. (2019) | | | | x |
| Tokimatsu, Yasuoka & Nishio. (2017) | x | | | |
| Wilberforce et al. (2019) | | | | x |

*Table 31: Literature review table biomass*

| | Availability | Potential | Netherlands |
|---|---|---|---|
| Elbersen et al. (2012) | x | x | x |
| Groth & Scholtens. (2016) | | x | x |
| De Jong et al. (2018) | | x | x |
| Van de Kaa, Kamp & Rezaei. (2017) | | x | x |
| Meijer et al. (2010) | | x | x |
| Scarlat et al. (2015) | x | x | |
| Thompson, Hermann & Hekkert. (2015) | | x | x |

# Appendix C: Carbon utilization project alternatives

The combination of the options and demand leads to a set of alternatives that need to be scored to determine the feasibility of carbon utilization for Meerlanden. The following alternatives are taken into the screening process.

### Methanol

Methanol (MeOH) production would be based on Emissions-to-Liquids technology (Carbon recycling, 2020). Captured CO2 can be transformed into Methanol by using hydrogen. There are two main sources for this hydrogen. Either as a by-product from other production processes or by using electrolysis to produce the hydrogen directly from the water. Figure 19 shows the generalized overview of the production process. There are two catalytic routes to synthesize MeOH from CO2. This can either be direct hydrogenation of CO2 with H2 or CO2 conversion into CO2 and further hydrogenation of CO (Pérez-Fortes & Tzimas, 2016). Methanol can be blended with gasoline up to 3%. Blends of 15% Methanol in gasoline are also already in use in China and 100% Methanol in light vehicles, buses, and trucks is also being stimulated in China(Carbon recycling international, 2020). Creating green Methanol can play a role in limiting the emissions of fossil-fuel-based vehicles.

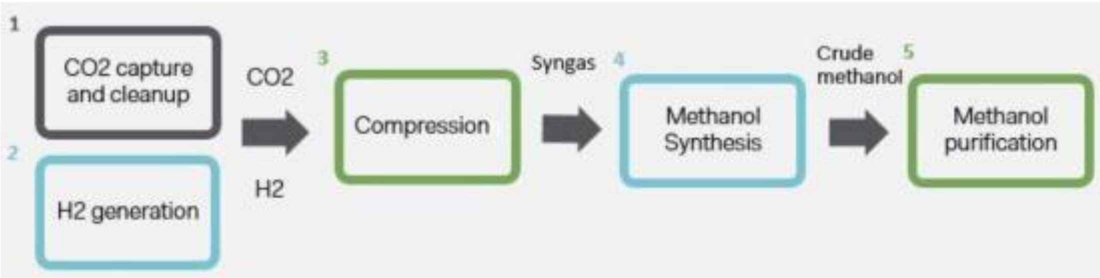


*Figure 19: Overall scheme of CRI and their CO2 to Methanol process (Green Car Congress, 2019)*

Pérez-Fortes & Tzimas (2016) provided an extensive financial analysis of the possibilities for a CO2 based Methanol plant. They estimate the Capital costs (investment costs) at 1281,77 €/ton MeOH/yr. The carbon capture installation at Meerlanden is estimated to provide around 10.000 ton CO2/yr. With the estimation that 1280 tCO2/tMeOH is used to produce the Methanol, this facility would be able to produce 7812 tMeOH/yr. With the metric of 1281,77 €/tMeOH/yr, the capital costs would be around 10 M€. Because of price reductions or unforeseen investment costs, a range of 9 to 11 M€ would give a proper estimation of possible required investment costs. Normalized investment costs are therefore €900 to €1100 per ton.

To assume the value of the product (MeOH), the comparison is made between 1 ton CO2 and the amount of 'product' can be made from it. 0,78 ton MeOH can be made from 1 ton CO2 and with a reference price of 350€/tMeOH, this gives it a value of around €275 (Pérez-Fortes & Tzimas, 2016). The added value of the Methanol plant will be around 245€/ton CO2.

The regionality of the Methanol plant is put at 4,5. Methanol can be blended with gasoline to create gasoline with fewer emissions compared to regular gasoline. Meerlanden has a relatively large fleet of vehicles consisting of garbage trucks, light trucks, heavy vehicles, and some 'regular' cars for business visits. Methanol could, therefore, be used, in theory, to lower the emissions of the fleet of vehicles. In practice, the garbage trucks use CNG will limit the possibilities for their use of Methanol. Methanol can also be blended into the gasoline for the stakeholding municipalities which significantly increases the potential demand for the produced Methanol. Either way, there is potential demand at Meerlanden and the shareholding municipalities which leads to a regionality score of 4,5.

Producing Methanol directly from CO2 can be a challenge. The product needs to be of high quality and the number of byproducts needs to be limited. Extensive complexity can be expected for products and variants. The method of production, when functioning properly, is expected to have high complexity but not extensive. Layout and equipment are also expected a have high complexity. The layout of the facility and the equipment required will all be relatively complex. In terms of organization and environment, high complexity is also expected. When the complexity of the different parameters is average, Methanol production is expected to have a CI of 6 out of 9. Table 32 shows the different parameter scores.

*Table 32: Complexity index of Methanol production*

| | Complexity index |
|---|---|
| Products and variants | 9 |
| Method | 5 |
| Layout and equipment | 5 |
| Organisation and environment | 5 |
| **Average CI** | 6 |

Even though Methanol made from CO2 with renewable hydrogen limits the CO2 emissions compared to regular Methanol, the potential for long term storage of CO2 is low. The Methanol will be used, relatively short after production, for combustion or in other production processes. This leads to the CO2 (either all or partial) being released back into the atmosphere. There will be less CO2 emissions compared to normal production but the CO2 captured at Meerlanden will not be taken out and stored for a long time to lower the CO2 in the atmosphere.

Currently, CO2 based Methanol production is found in a couple of places around the world: In Iceland with carbon recycling international and in Japan with Mitsui Chemicals (Pérez-Fortes & Tzimas, 2016). The plant in Iceland is ready for upscaling and received funding to scale its production (Green Car Congress, 2019). With the Mitsui Chemicals plant being of pilot-scale (<100 ton MeOH/yr), Carbon Recycling International in Iceland is the first implementation. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 7. Table 33 shows a summary of all the criteria of Methanol production at Meerlanden.

*Table 33: Summary of Methanol production*

| | Methanol |
|---|---|
| Investment costs | €900- €1100 |
| Value | €275 |
| Regionality | 4,5 |
| Complexity | 6 |
| Carbon storage | 0 |
| TRL | 7 |

## Ethanol

The electrochemical process of transforming CO2 into Ethanol is less developed then Methanol. Zeton and Air Company have developed a novel Ethanol Pilot plant (Zeton, 2019). They have developed a high yield catalyst that makes it possible to efficiently produce Ethanol from CO2. Ethanol can then be used in the food and beverage, flavors, and fragrances, and cosmetics industries. In May 2020 their second pilot plant was delivered to Turkey to be used by Turkish Petroleum Refineries Corporation (Zeton, 2020). The process that is used is shown in figure 20. The main difference between companies or research is the use of the catalyst. The catalyst helps in turning the syngas into the desired fuel and with the pilot of Zeton, they have found a catalyst that provides highly efficient ways of producing Ethanol from CO2.

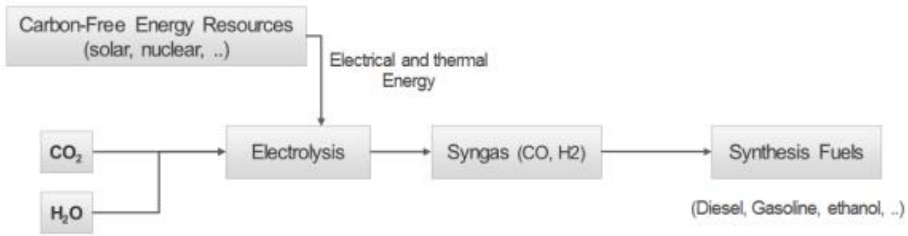


*Figure 20: Overall scheme of Ethanol production from CO2*

An estimation of the investment costs of a CO2 to Ethanol plant is provided by Gary Young, from bio-Thermal Energy Inc (Young, 2016). His estimation is based on a 21,3 Million gallon per year (80 million liters/year) Ethanol plant. With a weight of 0,79 kg/liter, puts the production capacity at 63200 ton/year. Based on the atomic weights of both CO2 and Ethanol and the formula for converting CO2 into Ethanol (Song *et al.,* 2016), 540 kg Ethanol can be made from 1 ton of CO2. This is with the assumption that all the CO2 can and will be converted into Ethanol. With the amount of CO2 available at Meerlanden (10000 tons), 5400 tons of Ethanol could be made, again with the assumption that all the CO2 will be converted. The CAPEX estimate by Young is 176 million dollars for the large Ethanol plant. When scaled to the possibilities at Meerlanden, an Ethanol plant would cost 15 million dollars (~12,5 million euros). The chance that the investment costs will be higher is large. Economies of scale less applicable because of the small size of the installation. A range between €12,5 million and 50% more expensive (€18,75 million) gives a plausible price range for a CO2 to Ethanol plant. Normalized investment costs range from €1250 to €1875 per ton.

As mentioned before, 1 ton of CO2 can be made into 540 kg Ethanol (with the assumption that all CO2 is converted). 540 kg Ethanol is equal to 684 liters (0,79 kg/liter) and with a price of 0,69 €/liter leads to €472 in value. Compared to the bare value of CO2 (30 €/ton) when delivered to greenhouses, gives Ethanol production an added value of around €440.

Ethanol is blended in with regular gasoline. Since last year, the standard amount of Ethanol has been increased to between 5% and 10%. This to decrease the CO2 emissions from cars and large vehicles. This also impacts the regionality of Ethanol production significantly. Ethanol can be used by Meerlanden to drive their vehicles but again, the garbage trucks (the main fuel consumers) are using CNG. In the stakeholding municipalities, there will be plenty of demand for Ethanol that potentially could be blended with regular gasoline. This gives a regionality score of 4,5.

The estimation of the complexity of the products and variants is high. Ethanol needs to be of a certain quality to be suitable for blending with regular gasoline. Furthermore, some byproducts could be expected and need to be limited. The method itself is also of high complexity. Ethanol production directly from CO2 can be difficult but when the facility is up and running, the complexity for Meerlanden will be limited to high. The facility itself, the layout, and equipment are also expected to be of high complexity. Organization and environment can also be expected to be of high complexity. Organization changes, the planning, and the different work tasks will all introduce new complexity to the business of Meerlanden. The average CI is expected to be 5 out of 9. Table 34 shows the different estimated parameter scores for the complexity indeed.

*Table 34: Complexity index of Ethanol production*

| | Complexity index |
|---|---|
| Products and variants | 5 |
| Method | 5 |
| Layout and equipment | 5 |
| Organization and environment | 5 |
| **Average CI** | 5 |

Carbon storage potential is almost the same as for Methanol. Producing Ethanol with renewable electricity will decrease the environmental impact of Ethanol but does not ensure longer-term storage of the captured CO2. After the Ethanol is used, the CO2 will be back in the atmosphere. This means that Ethanol production has no long-term carbon storage potential.

Zeton is investing in the development of technology to directly produce Ethanol from CO2. As mentioned before, since May 2020, the second pilot plant has been installed in Turkey. This can be described as an industrial pilot. The first pilot only produced 1 liter of Ethanol per hour, which was more of a demonstration pilot (Zeton, 2019). This proved that the technology worked and attracted interest. The second pilot will be part of a larger industrial system but can not be described as a first implementation. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 6. Table 35 shows a summary of all the criteria of Methanol production at Meerlanden.

*Table 35: Summary of Ethanol production*

| | Ethanol |
|---|---|
| Investment costs | €1250 - €1875 |
| Value | €472 |
| Regionality | 4,5 |
| Complexity | 5 |
| Carbon storage | 0 |
| TRL | 6 |

### Kerosene

The electrochemical conversion of CO2 into kerosene has great potential. With Schiphol close to Rijsenhout, all kerosene could be sold to be used to make the aviation sector more sustainable. At Rotterdam airport, there will be a small plant that can produce 1000 liter renewable kerosene per day (Joosse, 2019). Climeworks from Switzerland is the company that will retrieve the CO2 from the air. The process as described for Meerlanden will use almost the same process except for the source of the CO2, which will originate from the carbon capture installation. The CO2 will be transformed into syngas, thereafter into synthetic oil which will be further transformed into kerosene. Figure 21 shows the overall scheme of kerosene production from CO2.

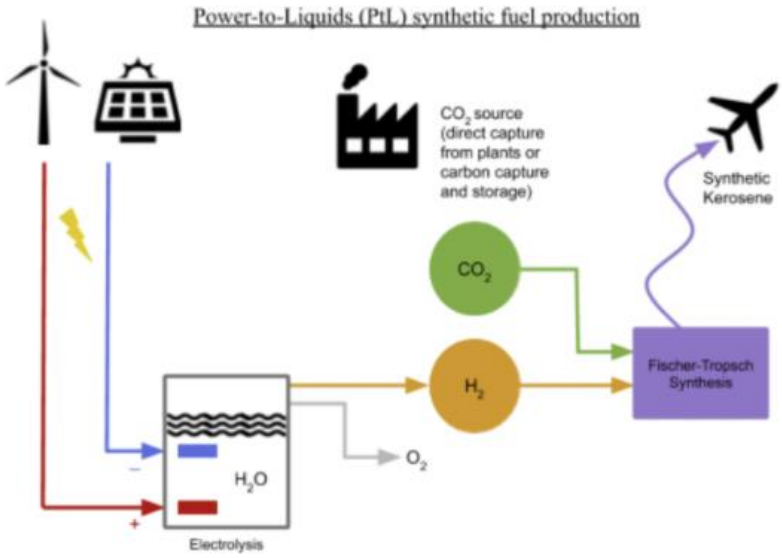


*Figure 21: Overall scheme of kerosene production from CO2 (Pieters, 2019)*

The production of kerosene directly from CO2 is only done on a pilot scale. There are plans to create larger plants to produce kerosene at a large enough scale that can have an impact on the aviation sector. A consortium of different companies (Norsk, Climeworks, Sunfire, etc) has plans to built a 100 million liters plant in Norway before 2026. They are starting with a demonstration plant in Porsfrunn with a production capacity of 10 million liters (Greenair, 2020) with an estimated investment of €90 million. As Kerosene consists of a blend of carbohydrates, it is more difficult to assess the amount of Kerosene that could be produced. With the assumption that the amount of CO2 emitted when burning kerosene is the same amount that is required to create renewable kerosene, an estimation can be made. 3 kg of CO2 will be emitted when burning kerosene, which means that 1 kg of CO2 is enough to produce 0,333 kg of kerosene (Engineering Toolbox, 2020). 10.000 ton CO2 available at Meerlanden would be enough to produce 3333 tons of kerosene (around 4 million liters). When plans of the consortium are scaled to the size of Meerlanden, the estimation will be €36 million as an investment cost. A plausible investment range will be between €30 million and €40 million for a 4 million liter plant. This is in line with the expectations of Yugo and Soler (2019). Normalized investment costs are therefore between €3000 and €4000 per ton.

As mentioned before, 0,333 tons of kerosene can be created from 1 ton of CO2. A reference price of $350 per ton (300 euro per ton), gives a value of €100 in kerosene per ton CO2 captured (IATA, 2020). The price of Kerosene is momentarily very low because of the pandemic and oil overproduction. There is a large chance that de price of kerosene will rise again to around 500 euro per ton. This leads to a range of between €100 and €160 of kerosene per captured ton of CO2. This gives the relatively low added value of the whole process of between €70 and €130 per ton kerosene compared to the €30 per ton value of CO2.

Meerlanden has no direct use for the possible produced kerosene. Instead, Schiphol would provide in the demand. As KLM signed a contract to buy at least 75% of the renewable kerosene (75000 tons) that will be produced in Delfzijl (Noordhollands Dagblad, 2019), they are interested in becoming more sustainable. 4000 tons from Meerlanden would decrease their CO2 emissions even further. Even though the supply is limited, there is almost no supply in renewable kerosene. Ever supply is therefore a welcome addition. As Schiphol is part of a stakeholding municipality (Haarlemmermeer), the regionality score would be set at 4.

Kerosene is made up of a range of hydrocarbons. This introduces extensive complexity in terms of products and variants. The method of creating kerosene from $CO_2$ also means an extra conversion step compared to other alternatives. The synthetic oil needs to be converted into kerosene to make it suitable for use. This leads to very high complexity in terms of method. This extra step also means additional complexity for the layout and equipment. The expectation is that this will also be very high complexity. The organization and environment are estimated at high complexity. The overall estimated CI of kerosene production comes to 7. Table 36 shows the parameters that make up the complexity index.

*Table 36: Complexity index of Kerosene production*

| | Complexity index |
|---|---|
| Products and variants | 9 |
| Method | 7 |
| Layout and equipment | 7 |
| Organization and environment | 5 |
| **Average CI** | **7** |

Renewable kerosene has a large impact on making the aviation sector more sustainable. Electric airplanes are being developed but will take at least a decade to become a reality. To make airplanes carbon-neutral, changing the fuel is now the only viable option. Even though the reduction in $CO_2$ emission is significant (Noordhollands Dagblad, 2019) with renewable kerosene, it has no possibilities to store $CO_2$ for a longer period. After combustion, the $CO_2$ will return to the atmosphere. The score will, therefore, be 0.

The possibilities are there and projects are being developed. As mentioned before, in 2022 (Delfzijl) and 2026 (Norway), significant amounts of renewable kerosene production should be available. The amount of production capacity sounds impressive but on a world scale, it could be described as industrial pilots. For now, TRL remains at 5 because of different demonstration pilots. Table 37 shows a summary of potential kerosene production at Meerlanden.

*Table 37: Summary of kerosene production*

| | Synthetic kerosene |
|---|---|
| Investment costs | €3000 - €4000 |
| Value | €100 - €160 |
| Regionality | 4 |
| Complexity | 7 |
| Carbon storage | 0 |
| TRL | 5 |

### Formic acid

Formic acid is the simplest carboxylic acid ($CH_2O_2$) and has a range of chemical applications. For Meerlanden can formic acid be particularly interesting because of the transport possibilities. Dens, a company based in Eindhoven has developed a formic acid-based bus and generator. They are scaling down their engine to be fit for more vehicles and applications (TU Eindhoven, 2018). Formic acid can in transport applications be used as a hydrogen carrier. This eliminates the need for compressing or difficult refueling processes. Furthermore, this could be fit for garbage trucks and carbon-neutral heavy transport. Dens is working on further developing the technology but the proven principle offers opportunities for Meerlanden. VoltaChem is working on the direct electrochemical conversion of $CO_2$ to formic acid which is the technology that would be used at Meerlanden (VoltaChem, 2020).

Pérez-Fortes & Tzimas (2016) not only made estimations for Methanol production but also Formic acid production. They base their estimations on an 8000 ton CO2 per year production facility that producing 12000 tons of formic acid. With the assumption that all CO2 at Meerlanden (10000 tons) is transformed into formic acid, 15000 tons could be produced. The CAPEX for the 12000-ton plant is estimated at €16 million. With an increase of 25%, the CAPEX should be €20 million. Development in electrolysis can lead to a relatively large decreasing in CAPEX. Besides these assumptions, there is a large possibility that €20 million is a low estimate. A plausible investment costs range should be between €16 million (the original estimate) and €25 million. €25 million is a 25% increase relative to the scaled-up estimate which would correct unforeseen expenses. Normalized investment costs are therefore between €1600 and €2500 per ton.

As previously described, 1 ton of CO2 (with the assumption that all CO2 is converted into formic acid) can be transformed into 1,5-ton formic acid. The reference price for formic acid is €650 per ton (Pérez-Fortes & Tzimas, 2016). This provides a value of €975 for the kerosene made from 1 ton of CO2. The added value of the whole process is hereby €945 compared to the value of CO2 when delivered to greenhouses.

The regionality of formic acid depends on the possibilities for Meerlanden and the stakeholding municipalities. If the technology from Dens gets more developed and provides the possibility to use formic acid as a fuel, the regionality increases significantly. If this is not the case, formic acid can still be put to good use. It is also used in the agricultural industry which could be the second-best option. To compensate for the fact that it is still unclear what the transport options for formic acid are, the regionality score is set at 4.

The production of formic acid will be directly from CO2 to formic acid. By-products, variants, and quality are of extensive complexity. The method itself is expected to be of high complexity. Again, it is difficult to implement but when this succeeds, the method will be 'less' complex. The layout and equipment are also expected to be of high complexity. Relatively new equipment and techniques tend to have high complexity which will also apply to the proposed formic acid facility. The organization and environment are also expected to be of high complexity. Changes in man-hour planning, the organization itself, and communication changes will have a significant impact on the business of Meerlanden. The expected CI is assumed at 6 within table 38 the parameters that make up the complexity index.

*Table 38: Complexity index of Formic acid production*

| | Complexity index |
|---|---|
| Products and variants | 9 |
| Method | 5 |
| Layout and equipment | 5 |
| Organization and environment | 5 |
| **Average CI** | 6 |

Formic acid produced from captured CO2 with renewable energy has significantly lower emissions compared to regular formic acid production (Pérez-Fortes & Tzimas, 2016). If it is used as fuel, agricultural industry, or in the chemical industry, the long-term carbon storage capacity is still low. After use, the CO2 will return to the atmosphere and is not stored for a long period. Therefore, the score is put at 0.

The TRL of formic acid production is relatively low compared to other alternatives. As mentioned before, VoltaChem is working on the direct electrochemical conversion of CO2 into formic acid. They developed and tested a reactor that will be scaled-up to a demonstration pilot at Twence in Hengelo (VoltaChem, 2019). At Twence, they already capture CO2 and they are planning to use this CO2 as a feedstock for the pilot plant. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 5. Table 39 shows a summary of all the criteria of Formic acid production at Meerlanden.

*Table 39: Summary of formic acid production*

| | Formic acid |
|---|---|
| Investment costs | €1600 - €2500 |
| Value | €975 |
| Regionality | 4 |
| Complexity | 6 |
| Carbon storage | 0 |
| TRL | 5 |

**Compensatiesteen**

The Compensatiesteen is an initiative from the Ruwbouw Groep. It is an innovative building material that is best suited as a building block for walls in the housing and utility construction (Ruwbouw Groep, n.d.). The bricks are made from sand, granulates, and a secondary additive as a binding agent. Instead of heat to dry the bricks, CO2 is used. By using large amounts of CO2, the natural process of carbonatation is accelerated. The CO2 gets permanently bound to the bricks and the process creates a structure that is similar to hard limestone found in nature. During this process, 250 kg CO2/$m^3$ Compensatiesteen gets bonded. Figure 22 shows the production process of Compensatiesteen.

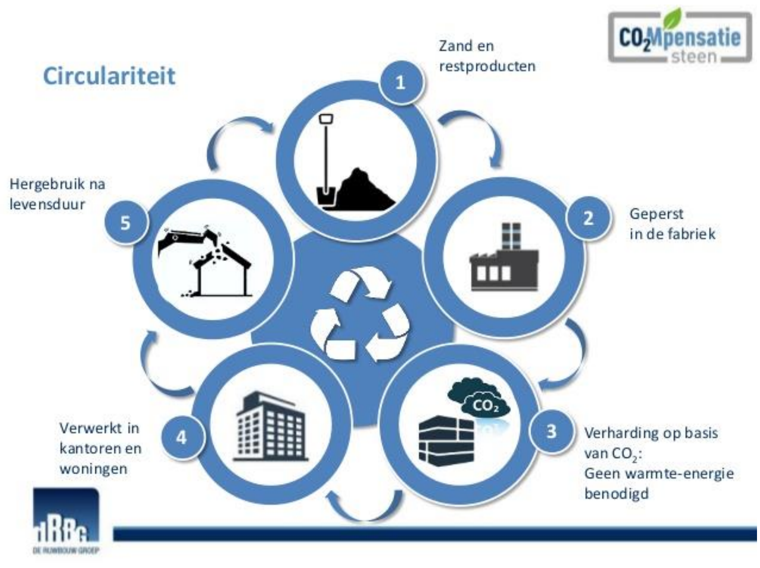


*Figure 22: The process of the Compensatiesteen (Ruwbouw Groep, 2017)*

There are no similar facilities as a reference for such a facility. Other producers create stone-like products from CO2 but they differ greatly in terms of the production process. Frans Temmermans, from the Ruwbouw Groep, gave more insight into the costs involved with the Compensatiesteen. Exact numbers could not be made public but, based on the amount of CO2 available and the desired plant size, the investment costs would be in the millions. Additional and more concrete references are required to give a more valid estimation. In 2006, a sand-lime brick factory planned in Oosterhout has received an investment of €20 million (NV Rewin West-Brabant, 2006). The initial capacity was put at enough sand-lime stone for the construction of 5000 houses per year with the potential to scale up the production capacity, which is similar to the proposed Compensatiesteen production. The factory requires 6 ha of land area and offers 30 jobs. The process of producing sand-lime stone brick is traditionally dependent on high temperatures and thereby different from Compensatiesteen production. Furthermore, there is a large difference between the confirmed investment by Rewin and the comments made by the expert from the Ruwbouw group, Frans Temmermans. An investment cost range will therefore be used to account for this difference. The estimation will be that an investment made into a Compensatiesteen facility will be between €8.000.000 and €12.000.000. This is based on the scaling of the Rewin facility to the proposed Meerlanden facility. Because the technology is different, a range of 50% investment cost increase is added. Normalized investment costs are between €800 and €1200 per ton.

250 kg of CO2 per $m^3$ can be stored in the Compensatiesteen during the production process. This means that 1 ton of CO2, when all the CO2 is stored during the process, is sufficient to create 4 $m^3$ of Compensatiesteen. As prices of the Compensatiesteen are not available, the comparison will be made using normal bricksas a price reference. Normal sand-limestone bricks (similar characteristics as the Compensatiesteen) are available from €1,19 and 4 $m^3$ contains around 550 bricks. This puts the value of 1 ton captured CO2 transformed into Compensatiesteen at €650. The added value of the process is €620 compared to the base price of CO2.

Meerlanden has no direct use for such a product as the Compensatiesteen. Maybe new facilities or office space can make use of their product but this will not be sufficient to fulfill the total demand. Based on 10000 ton CO2 and the assumption that the facility is large enough, 40000 $m^3$ of Compensatiesteen can be created. The stakeholding municipalities have plans to built around 30000 new houses in the area over Rijsenhout. Over a period of 10 years, the Compensatiesteen produced at Meerlanden can supply a significant portion of the required bricks of the to be built houses. This put the regionality score at 4.

Products and variants are expected to be of medium complexity. The first focus will be on creating a single type of limestone brick which can later, possibly, be extended with other shapes and sizes. The method of production is also expected to be of medium complexity. It will involve heavy equipment but the process itself is not so complex (compared to other alternatives). The layout and equipment are also expected to be of medium complexity. The facility itself will be of relatively low complexity and heavy equipment is already available which limits the overall complexity. The organization and environment are also to be expected of medium complexity. The production process will require additional planning and personnel but nothing that Meerlanden is not already used to doing. The overall CI will be 3, which is medium complexity. The overall score of the different parameters is shown in table 40.

*Table 40: Complexity index of Compensatiesteen production*

| | Complexity index |
|---|---|
| Products and variants | 3 |
| Method | 3 |
| Layout and equipment | 3 |
| Organization and environment | 3 |
| **Average CI** | 3 |

As mentioned before, the production process uses $CO_2$ to create a permanent binding. This defines the principle of long-term storage. The $CO_2$ is stored and will not be released until the stones get recycled or destroyed. With average houses being built for at least 50 years (more likely 100 years), captured $CO_2$ at Meerlanden which is uses to produce the Compensatiesteen will be out of the atmosphere for a very long time.

The TRL of Compensatiesteen production is relatively high, even though it is a 'new' product. They have passed the industrial pilot and are now running the first implementation of their production process in Zwolle. Certification of the bricks is also approved and certification is also pending for the use of the bricks as supporting walls. This last certification would drastically increase the possibilities and eventually, demand. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 7. Table 41 shows a summary of all the criteria of Compensatiesteen production at Meerlanden.

*Table 41: Summary of Compensatiesteen production*

| | Compensatiesteen |
|---|---|
| Investment costs | €800 - €1200 |
| Value | €650 |
| Regionality | 4 |
| Complexity | 3 |
| Carbon storage | 1 |
| TRL | 7 |

### Food industry

In 2015, 228 billion liters of soft drinks were consumed (Air Liquide, n.d.). Soft drinks are just a part of the food and beverage products that require $CO_2$ to be produced. $CO_2$ for the food and beverage industry mainly originates from ethanol and ammonia producers. When these installations stop producing, there is a limited supply of good grade $CO_2$ available. In 2018, the UK (and other parts of Europe) faced a shortage of food-grade $CO_2$ because of higher demand and limited supply. Breakdowns at UK ammonia producers and bioethanol plants being offline for maintenance were the main reasons that a shortage occurred (Fortune, 2019). Captured $CO_2$ at Meerlanden could become another supplier of food-grade $CO_2$. Frames, the proposed manufacturer of the carbon capture installation, shows that with the current specification a high purity of $CO_2$ can be achieved. Depending on the specifications and demand, 'food-grade' quality may or may not be possible directly (Frames, 2020). Otherwise, an additional purification process will be needed to produce food-grade quality. This possible additional step affects the OPEX of the process and will thereby change the business case of the project alternative. Furthermore, compression will also be required to transport and use the $CO_2$ in the food and beverage industry.

Gas balloons will be required when implementing the food-industry alternative. According to Frames, this will cost 500.000 to construct. These gas balloons are for the storage of the food-grade $CO_2$. Depending on the specifications and characteristics of the captured $CO_2$, further purification will be needed. The assumption is that these costs will be another €500.000 to install. Oi *et al* (2016) put the CAPEX for compression of 1 million tons/yr $CO_2$ facility at €23 million. 10.000 tons per year at Meerlanden is 1% but because of economies of scale, the estimation is that the scaled range will be between 1% and 2%. The investment costs range will, therefore, be between €730.000 and €1.460.000. Normalizing the investment costs gives a value of between €73 and €146 per ton.

The assumption is that every ton of $CO_2$ captured can be used and sold to other customers without losses during purification or transport. This puts the value of 1 ton of captured $CO_2$ at between €80 and €150 per ton of $CO_2$ (Mikunda *et al.,* 2015).

Meerlanden has no direct use for food-grade $CO_2$, just as stakeholding or service municipalities. There is, however, a demand for food-grade $CO_2$ in the Netherlands with large food and beverage producers located around the Netherlands. Potential shortages in the future, this creates an even larger potential but transport will be required to other parts of the Netherlands. In the region of Rijsenhout or the stakeholding municipalities, there are no large producers that require food-grade $CO_2$. The regionality score will, therefore, be 2.

The main issue of producing compressed $CO_2$ for the food and beverage industry is the requirement of food-grade quality. The proposed facility either can already produce food-grade $CO_2$ or will require minimum purification. This leads to an estimation of medium complexity for products and variants. The method in itself is of minor complexity. The carbon capture installation provides the $CO_2$ that only needs to be compressed. The layout and equipment are therefore also of minor complexity. The organization and environment are also expected to have minor complexity. The organization and planning require minimum changes to deal with the implementation of liquefication for food-grade compressed $CO_2$. The average CI comes down to 1,5, which is minor complexity of the whole production process. Table 42 shows the parameters of the complexity index.

*Table 42: Complexity index of the food industry*

| | Complexity index |
|---|---|
| Products and variants | 3 |
| Method | 1 |
| Layout and equipment | 1 |
| Organization and environment | 1 |
| **Average CI** | 1,5 |

The long-term carbon storage potential is non-existent. $CO_2$ in beverages escapes when consumed which will return to the atmosphere. It also does not lower the $CO_2$ emissions in the food and beverage industry as they are already using the $CO_2$ which is produced as a by-product from different processes. The score for carbon storage will be a 0.

The TRL of providing $CO_2$ to the food and beverage industry is high. This practice has been done all over the world with different chemical processes. Even though producing food-grade $CO_2$ from carbon capture at a biomass plant will be relatively new, the capture and purifying have been done before. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 9. Table 43 shows a summary of all the criteria of the food industry alternative at Meerlanden.

*Table 43: Summary of food industry alternative*

| | Food industry |
|---|---|
| Investment costs | €73 - €146 per ton |
| Value | €80 - €150 per ton |
| Regionality | 2 |
| Complexity | 1,5 |
| Carbon storage | 0 |
| TRL | 9 |

## Textile industry

The use of $CO_2$ in the textile industry is relatively new. The textile industry has two main processes in which $CO_2$ can be used: textile coloring and washing. Dyecoo has developed a technology for dyeing polyester fabrics and has been embraced by major brands like Ikea and Nike (DyeCoo, 2020). Their 130 industrial textile coloring equipment has a daily capacity of 4000 kg of textiles. The main advances of their process are that it uses zero water and recycles 95% of the $CO_2$ after each batch. Washing of textiles with $CO_2$ uses somewhat of a similar process. Using $CO_2$ instead of water to deep clean textiles. The main drawback of supplying $CO_2$ to the textile industry will be that other companies have to commit to the technology. This will require large investments that other companies will have to make. Furthermore, compression will be required to supply compressed $CO_2$ instead of gaseous $CO_2$.

The alternative will require gas balloons for storage, priced at €500.000 by Frames. Furthermore, the compression will require additional equipment. Oi *et al* (2016) put the CAPEX for compression of 1 million tons/yr $CO_2$ facility at €23 million. 10.000 tons per year at Meerlanden is 1% but because of economies of scale, the estimation is that the scaled range will be between 1% and 2%. Combined with the investment costs of the gas balloons, the investment will be between €730.000 and €960.000 to be able to supply $CO_2$ to the textile industry. The normalized investment costs come down to between €73 and €96 per ton.

The value of compressed $CO_2$ for the textile industry will be dependent on the market price for compressed supercritical $CO_2$. Furthermore, the purity of the compressed $CO_2$ is less important than for the food industry. Food-grade quality is not required and therefore, the $CO_2$ will sell for the normal market price. The price will be between €80 and €150 per ton, depending on a range of factors (Mikunda *et al.,* 2015).

The potential for use of $CO_2$ in the textile industry and the regionality is relatively high. Meerlanden has no direct use or interest in this kind of process. The area around Rijsenhout however, is filled with companies involved in the textile industry. Mainly the drycleaning (washing) of textile for Schiphol and Amsterdam is located in stakeholding municipalities. This will require investments from these companies to be able to use $CO_2$ for their processes but in potential, the regionality can be high. This leads to a score of 4 in terms of regionality.

The textile industry needs compressed $CO_2$ to be able to use it for the proposed alternative processes. This limits the complexity of the products and variants to minor as the quality is less of an issue compared to the food and beverage industry. The method itself is also of minor complexity. Captured $CO_2$ is compressed and stored for transport to the customers. Layout and equipment are also expected to be of minor complexity for Meerlanden. The compression installation is of limited size and does not require additional high complexity equipment. Organization and environment are also expected to be of minor complexity. Additional planning will be required in terms of man-hour and transport but it is all in line with what Meerlanden already does. The overall CI comes down to minor complexity. Table 44 shows the different parameters for the expected complexity of the textile industry.

*Table 44: Complexity index of the textile industry*

| | Complexity index |
|---|---|
| Products and variants | 1 |
| Method | 1 |
| Layout and equipment | 1 |

| | |
|---|---|
| Organization and environment | 1 |
| **Average CI** | 1 |

The long-term carbon storage potential of the process is low. Some processes, like DyeCoo, will recycle a large part of the required CO2 (95% per batch) but with a lot of batches, all the CO2 will enter the atmosphere in a relatively short period. The savings of these processes are in low to zero water usage but this does not impact the CO2 storage potential. The score for carbon storage is therefore 0.

The TRL of providing CO2 to the textile industry is high. Processes involved in the coloring or washing with CO2 are relatively new but this does not account for the process of capturing and compressing CO2. This has been done at multiple different processes and installations. According to figure 11 in chapter 2.3.1.6, the Technology Readiness Level can be put at 9. Table 45 shows a summary of all the criteria of the textile industry alternative at Meerlanden.

*Table 45: Summary of textile industry alternative*

| | Textile industry |
|---|---|
| Investment costs | €73 - €96 |
| Value | €80 - €150 per ton |
| Regionality | 4 |
| Complexity | 1 |
| Carbon storage | 0 |
| TRL | 9 |

# Appendix D: Analytical hierarchy process

Questionnaire AHP

## Analytisch hiërarchisch proces

Voor het bepalen van de gewichten van de verschillende criteria voor het selecteren van de project alternatieven is input nodig van Meerlanden. Dit gebeurt aan de hand van het Analytisch hiërarchisch proces. Hiermee word de score bepaald welke alternatieven verder mee genomen worden in de studie naar het bepalen van de potentiële effecten van carbon utilization.
De criteria die mee genomen worden en waarvan de gewichten moeten worden bepaald zijn als volgt:

Investeringskosten: De CAPEX van een project.
Waarde product: De waarde van een product dat gemaakt kan worden van de afgevangen CO2
Regionaliteit product: Hoe dichter bij Meerlanden het product gebruikt kan worden, hoe beter de score op regionaliteit.
Complexiteit productie proces: Een zeer complex productie proces is ongewenst voor Meerlanden.
Lange termijn opslag CO2: CO2 voor een langere periode opslaan heeft een groter effect bij het reduceren van de CO2 uitstoot.
Technology Readiness Level: Dit criteria geeft aan in hoeverre de technologie ontwikkeld is en daarmee ook klaar is voor commerciele implementatie.

U word gevraagd om steeds twee criteria met elkaar te vergelijken. Selecteert u dan welke van de twee belangrijker is (of gelijkwaardig) en geeft u dan vervolgens aan in welke mate één van de twee criteria belanrijker is. Bij gelijkwaardige criteria is slechts de selectie van deze optie genoeg. Bij de andere situaties selecteert u of het eerste of twee vakje en vervolgens één van de laatste vier vakjes (iets belangrijker, belangrijker, veel belangrijker of extreem veel belangrijker).

1. Investeringskosten vs waarde product

*Vink alle toepasselijke opties aan.*

- ☐ Investeringskosten belangrijker
- ☐ Waarde product belangrijker
- ☐ Gelijkwaardige criteria
- ☐ Iets belangrijker
- ☐ Belangrijker
- ☐ Veel belangrijker
- ☐ Extreem veel belangrijker

2. Investeringskosten vs regionaliteit product

*Vink alle toepasselijke opties aan.*

- [ ] Investeringskosten belangrijker
- [ ] Regionaliteit product belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

3. Investeringskosten vs complexiteit productie proces

*Vink alle toepasselijke opties aan.*

- [ ] Investeringskosten belangrijker
- [ ] Complexiteit productie proces belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

4. Investeringskosten vs lange termijn opslag CO2

*Vink alle toepasselijke opties aan.*

- [ ] Investeringskosten belangrijker
- [ ] Lange termijn opslag CO2 belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

5. Investeringskosten vs Technology Readiness Level

*Vink alle toepasselijke opties aan.*

- [ ] Investeringskosten belangrijker
- [ ] Technology Readiness Level belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

6. Waarde product vs regionaliteit product

*Vink alle toepasselijke opties aan.*

- [ ] Waarde product belangrijker
- [ ] Regionaliteit product belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

7. Waarde product vs complexiteit productie proces

*Vink alle toepasselijke opties aan.*

- [ ] Waarde product belangrijker
- [ ] Complexiteit productie proces belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

8. Waarde product vs lange termijn opslag $CO_2$

*Vink alle toepasselijke opties aan.*

- [ ] Waarde product belangrijker
- [ ] Lange termijn opslag $CO_2$ belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

9. Waarde product vs Technology Readiness Level

*Vink alle toepasselijke opties aan.*

- [ ] Waarde product belangrijker
- [ ] Technology Readiness Level belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

10. Regionaliteit product vs complexiteit productie proces

*Vink alle toepasselijke opties aan.*

- [ ] Regionaliteit product belangrijker
- [ ] Complexiteit productie proces belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

11. Regionaliteit product vs lange termijn opslag CO2

*Vink alle toepasselijke opties aan.*

- [ ] Regionaliteit product belangrijker
- [ ] Lange termijn opslag CO2 belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

12. Regionaliteit product vs Technology Readiness Level

*Vink alle toepasselijke opties aan.*

- [ ] Regionaliteit product belangrijker
- [ ] Technology Readiness Level belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

13. Complexiteit productie proces vs lange termijn opslag CO2

*Vink alle toepasselijke opties aan.*

- [ ] Complexiteit productie proces belangrijker
- [ ] Lange termijn opslag CO2 belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

14. Complexiteit productie proces vs Technology Readiness Level

*Vink alle toepasselijke opties aan.*

- [ ] Complexiteit productie proces belangrijker
- [ ] Technology Readiness Level belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

15. Lange termijn opslag $CO_2$ vs Technology Readiness Level

*Vink alle toepasselijke opties aan.*

- [ ] Lange termijn opslag $CO_2$ belangrijker
- [ ] Technology Readiness Level belangrijker
- [ ] Gelijkwaardige criteria
- [ ] Iets belangrijker
- [ ] Belangrijker
- [ ] Veel belangrijker
- [ ] Extreem veel belangrijker

## Appendix E: Sensitivity analysis FCBA

Table E1: Cost-benefit analysis with changes in investment cost (low investment cost)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-8,0** | **-16,0** |
| **Change in operating costs** | **-64,9** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **5,4** | **-145,4** |

Table E2: Cost-benefit analysis with changes in investment cost (high investment cost)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-12,0** | **-25,0** |
| **Change in operating costs** | **-64,9** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **1,4** | **-154,4** |

Table E3: Cost-benefit analysis with changes in raw material costs (low raw material costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-50,1** | **-223,6** |
| Change in raw material cost | -14,8 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **18,2** | **-149,9** |

Table E4: Cost-benefit analysis with changes in raw material costs (high raw material costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-79,7** | **-223,6** |
| Change in raw material cost | -44,4 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **-11,4** | **-149,9** |

Table E5: Cost-benefit analysis with changes in binding agent costs (low binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-56,7** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -8,2 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **11,6** | **-149,9** |

Table E6: Cost-benefit analysis with changes in binding agent costs (high binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-73,1** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -24,7 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **-4,8** | **-149,9** |

Table E7: Cost-benefit analysis with large changes in binding agent costs (far lower binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-50,1** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -1,6 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **18,2** | **-149,9** |

Table E8: Cost-benefit analysis with large changes in binding agent costs (far high binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-212,8** | **-223,6** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -164,4 | |
| Change in electricity cost | -1,2 | -47,0 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **-144,5** | **-149,9** |

Table E9: Cost-benefit analysis with changes in electricity costs (low electricity costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-64,3** | **-200,1** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -23,5 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **4,0** | **-126,3** |

Table E10: Cost-benefit analysis with changes in electricity costs (high electricity costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-65,5** | **-247,1** |
| Change in raw material cost | -29,6 | |
| Change in binding agent cost | -16,4 | |
| Change in electricity cost | -1,2 | -70,6 |
| Change in personnel cost | -6,8 | |
| Change in other costs | -10,9 | -176,6 |
| **Change in product revenue** | **78,3** | **94,3** |
| **FCBA total** | **2,8** | **-173,4** |

# Appendix F: Sensitivity analysis SCBA

Table F1: Cost-benefit analysis with changes in $CO_2$ pricing ($CO_2$ price at 100€/ton)

| Project effects \| Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-76,9** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **34,4** | **37,1** |
| Environmental benefits | 35,2 | 37,5 |
| Environmental costs | -0,8 | -0,3 |
| **SCBA total** | **40,3** | **-136,7** |
| **FCBA total** | **5,9** | **-173,8** |

Table F2: Cost-benefit analysis with changes in $CO_2$ pricing ($CO_2$ price at 200€/ton)

| Project effects \| Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-76,9** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **69,0** | **74,3** |
| Environmental benefits | 70,4 | 74,9 |
| Environmental costs | -1,5 | -0,6 |
| **SCBA total** | **74,9** | **-99,5** |
| **FCBA total** | **5,9** | **-173,8** |

Table F3: Cost-benefit analysis with changes in investment cost (low investment cost)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-8,0** | **-16,0** |
| **Change in operating costs** | **-76,9** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **18,2** | **-158,2** |
| **FCBA total** | **7,9** | **-169,3** |

Table F4: Cost-benefit analysis with changes in investment cost (high investment cost)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-12,0** | **-25,0** |
| **Change in operating costs** | **-76,9** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **14,2** | **-167,2** |
| **FCBA total** | **3,9** | **-178,3** |

Table F5: Cost-benefit analysis with changes in raw material costs (low raw material costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-59,4** | **-265,0** |
| Change in raw material cost | -17,5 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **33,7** | **-162,7** |
| **FCBA total** | **23,4** | **-173,8** |

Table F6: Cost-benefit analysis with changes in raw material costs (high raw material costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-94,5** | **-265,0** |
| Change in raw material cost | -52,6 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **-1,4** | **-162,7** |
| **FCBA total** | **-11,6** | **-173,8** |

Table F7: Cost-benefit analysis with changes in binding agent costs (low binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-67,2** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -9,7 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **25,9** | **-162,7** |
| **FCBA total** | **15,6** | **-173,8** |

Table F8: Cost-benefit analysis with changes in binding agent costs (high binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-86,7** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -29,2 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **6,4** | **-162,7** |
| **FCBA total** | **-3,8** | **-173,8** |

Table F9: Cost-benefit analysis with large changes in binding agent costs (far lower binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-59,4** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -1,9 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **33,7** | **-162,7** |
| **FCBA total** | **23,4** | **-173,8** |

Table F10: Cost-benefit analysis with large changes in binding agent costs (far high binding agent costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-252,2** | **-265,0** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -194,8 | |
| Change in electricity cost | -1,4 | -55,7 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **-159,1** | **-162,7** |
| **FCBA total** | **-169,4** | **-173,8** |

Table F11: Cost-benefit analysis with changes in electricity costs (low electricity costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-76,2** | **-237,2** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -0,7 | -27,9 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **16,9** | **-134,8** |
| **FCBA total** | **6,6** | **-145,9** |

Table F12: Cost-benefit analysis with changes in electricity costs (high electricity costs)

| Project effects / Alternative | Compensatiesteen | Formic acid |
|---|---|---|
| **Change in investment costs** | **-10,0** | **-20,5** |
| **Change in operating costs** | **-77,6** | **-292,9** |
| Change in raw material cost | -35,1 | |
| Change in binding agent cost | -19,5 | |
| Change in electricity cost | -2,1 | -83,6 |
| Change in personnel cost | -8,1 | |
| Change in other costs | -12,9 | -209,3 |
| **Change in product revenue** | **92,8** | **111,7** |
| **Environmental effects** | **10,3** | **11,1** |
| Environmental benefits | 10,6 | 11,2 |
| Environmental costs | -0,3 | -0,1 |
| **SCBA total** | **15,5** | **-190,6** |
| **FCBA total** | **5,2** | **-201,7** |